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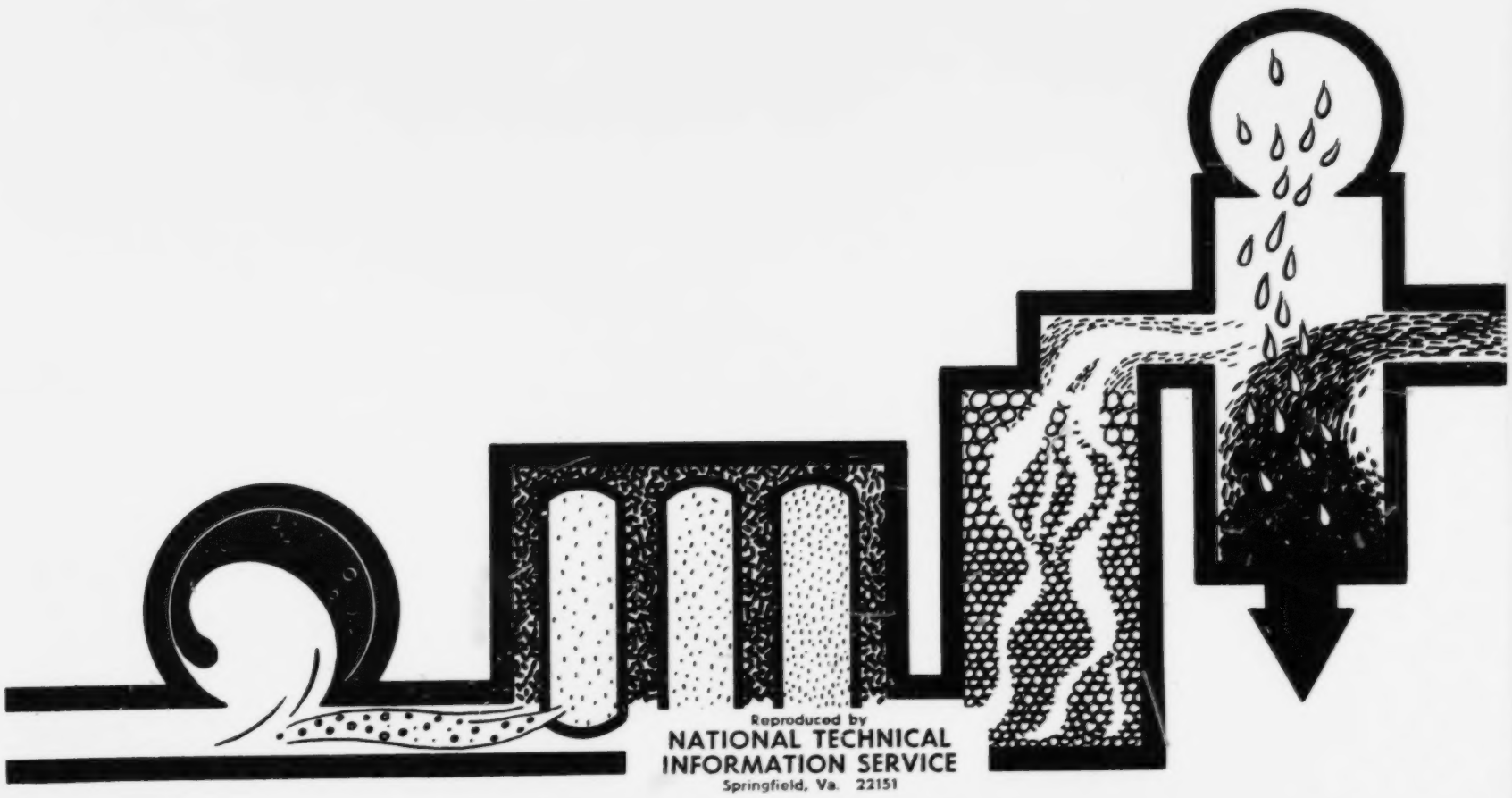

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27 Abstract

An experimental program was conducted to determine equipment configurations for efficient solids removal, identification of critical parameters involved in the efficiency of electroosmotic pumping, and the design and testing of two prototype electroosmotic pumps. It was determined that electroosmosis can be applied to dewatering waste sludges of various types. For efficient dewatering from very wet sludge (2%) to burnable solids, it is necessary to orient the pumping apparatus with a cathode screen beneath the anode so that an initial sludge film can be formed by gravity settling at the cathode surface. Sludge cannot be thickened to a solids level exceeding 20% if the cake is beneath the liquid level of the sludge suspension and for drying beyond the 20% value, the cake must be brought out of the liquid. (Ellis-Texas)

(WRSIC abstract)

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ELECTROOSMOTIC PUMPING FOR DEWATERING SEWAGE SLUDGE

by

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for the

FEDERAL WATER QUALITY ADMINISTRATION

DEPARTMENT OF THE INTERIOR

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ABSTRACT

Electroosmotic pumping derives from the electrokinetic phenomenon of electroosmosis, i.e., the flow of water through porous matrices or constrained suspensions of fine particles that is produced by an applied electric field. Electroosmotic pumping is theoretically independent of the cross-sectional area of the pore structure of the filtering media. Thus, the inherent limitations of conventional filtration resulting from pore clogging or filter cake compression are minimized, and electroosmotic pumping provides a technique for dewatering hard-to-filter materials. An investigation of electroosmosis for application to dewatering waste sludges to a solids level sufficient for auto-incineration has been carried out.

The feasibility program consisted of investigation of electroosmotic flow in sewage sludge suspensions and identification of parameters critical to efficient electroosmotic pumping under varying conditions of applied voltage, current flow, and variability of the surface properties of the sludge solids. Appropriate configurations for pumping apparatus were investigated through design and testing of prototype electroosmotic pumps, and new electrode materials were tested for anode service in electroosmosis.

It has been determined that electroosmosis can be applied to dewatering waste sludges of various types. For efficient dewatering from very wet sludge (2%) to burnable solids, it is necessary to orient the pumping apparatus with a cathode screen beneath the anode so that an initial sludge film can be formed by gravity settling at the cathode surface. Sludge cannot be thickened to a solids level exceeding 20% if the cake is beneath the liquid level of the sludge suspension; for drying beyond the 20% value, the cake must be brought out of the liquid.

Electroosmotic pumping is slow. Thus, large electrode surface areas are required for pumping productivity to keep pace with a typical treatment plant's sludge production. However, the development of stannic oxide for anode service is expected to reduce projected electrode costs. Furthermore, in tandem with a pre-thickening process, the rate of dewatering by electroosmosis becomes less critical. Operating costs for electroosmotic dewatering appear to be promising for sludges with solids contents of 6% or greater, further suggesting that electroosmosis may be more practically used as a process in tandem with a pre-thickening stage.

This report was submitted in fulfillment of Contract 14-12-568 between the Federal Water Quality Administration and the Rocketdyne Division of North American Rockwell Corporation. The content of the report is a summary of work carried out under Contracts 14-12-406 and 14-12-568 during the period 24 June 1968 through 23 July 1970.

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CONCLUSIONS

General conclusions that may be drawn from the results of the investigation are as follows:

1. Electroosmosis can be applied to dewatering sewage treatment and water treatment sludges of various types.

2. For efficient dewatering from very wet sludge (2%) to burnable solids, it is necessary to orient the pumping apparatus with the cathode screen beneath the anode so that an initial sludge film can be formed by gravity filtering at the cathode surface. However, starting with pre-concentrated sludges that are less liquid in character, the formation of an initial film is not necessary.

3. Sludges cannot be thickened to a solids content exceeding 20% if the cake is beneath the liquid level of the sludge suspension. For drying beyond the 20% values, the cake must be brought out of the liquid.

4. The operating costs for electroosmotic dewatering appear to be promising for sludges with solids contents of 6% or greater, suggesting that the use of electroosmosis in tandem with a prethickening process may be more attractive than using it alone.

5. Experiments with prototype apparatus indicated that electroosmotic pumping is slow. Average pumping rates of 3.5 $ml/hr/cm^2$ (0.8 $gal/hr/ft^2$) of electrode surface were observed. Thus, large electrode surface areas are required if pumping productivity is to keep pace with a typical treatment plant's sludge production. However, preconcentration of sludge suspensions can reduce the electrode area requirements.

6. Stannic oxide ceramics are oxidation resistant and can be used to advantage in anode service in electroosmotic pumping.

RECOMMENDATIONS

The major purpose of the investigation described herein was to assess the feasibility of applying the phenomenon of electroosmosis to dewatering sewage treatment sludges. It was not within the scope of the program to attempt scale-up of apparatus to pilot plant sized units. Sufficient information has been obtained to indicate that electroosmosis holds promise as a sewage treatment unit process, particularly in view of the discovery that anodes for electroosmotic pumping could be constructed from conductive stannic oxide ceramics, thus reducing projected equipment costs. However, the practicality of the process, in terms of operating economics and efficiency, remains to be properly assessed. Such assessment can be made only through continued study of the process in pilot plant sized equipment. It is recommended that such a study be carried out.

INTRODUCTION

The ultimate disposal of waste sludge is a problem of major proportions with one of the more significant contributors being dewatering. With convenient and economic dewatering techniques, the intrinsic fuel value of the sludge can often be used to carry out final disposal by incineration. Unfortunately, few sludges lend themselves to convenient or economic dewatering by conventional techniques, primarily because these techniques are generally dependent upon the hydraulic permeability or the settling characteristics of the sludge suspensions. It is the objective of this report, therefore, to describe an investigation of electroosmotic pumping, a sludge dewatering method with promise for more general water removing capability.

Electroosmosis is a physical chemical phenomenon discovered over 150 years ago by Reuss (1809) who observed that if an electrical potential is applied to a porous diaphragm, water moves through the diaphragm capillaries toward the cathode; and that as soon as the electric current is stopped, the flow of water stops. The basis for the flow is the presence of a "double layer" at the walls of the capillary. That is, a distinction can be made between free water and a boundary film of water immediately adjacent to the capillary walls that is thin relative to the capillary diameter. Surface chemists call the boundary film the double layer because it is assumed that there is a separation of electric charges on the two surfaces of the film. One surface normally carries a charge that is rigidly attached to the wall, and the other surface carries a diffuse distribution of opposite charge that is movable. Thus, if an electric potential is applied to the ends of the capillary, the diffuse charges can move toward one pole. In doing so, they can drag along the water molecules of the movable part of the film and the cylinder of free water that the film encloses.

A similar phenomenon occurs in the liquid phase of suspensions of small particles. When the movement of the solid phase is constrained, water flows under the influence of an applied field because of the existence of the double layer at the surfaces of the particles. Furthermore, as will be seen, the velocity of the flow is dependent only on the magnitude of the applied field and is essentially independent of the state of compression of the suspension. It is the latter property that makes electroosmosis a potentially attractive sludge dewatering technique.

It can be shown that the quantity of liquid moved in unit time by electroosmosis in a single capillary is given by the equation[1]

$$q_e = \frac{EDr^2Z}{4\,L\,v} \qquad (1)$$

where E is the electrical potential, D the dielectric constant of the liquid, r the radius of the capillary, Z the electrokinetic or zeta potential, which is defined as the potential existing between the rigid and the moval parts of the double layer, L the length of the capillary between the electrodes, and v the viscosity of the liquid.

The electrokinetic potential Z is characteristic of a specific surface and solution. Thus, variations in solution pH or ionic strength can affect Z. For example, an increase in pH would tend to neutralize a negatively charged surface and reduce Z[2]. However, for a given system, one can consider the quantity $DZ/4\pi v$ constant. Also, one can define the potential gradient $E/L = \epsilon$, and $\pi r^2 = a$ = cross sectional area of the capillary. Multiplying and dividing Eq. 1 by π then, one obtains

$$\frac{qe}{a} = V_e = C_e\,\epsilon \qquad (2)$$

where V_e, the flow velocity, is seen to be independent of the capillary size for a fixed value of Z.

In contrast to electroosmotic flow, ordinary hydraulic flow is dependent on capillary diameter. That is, since flow in a hydraulic filter is almost always laminar, it can be described by the Hagen-Poiseuille equation (McCabe, 1956). By analogy to the example above then, the velocity in a long capillary is given by

$$V_h = C_h\,\Phi\,a \qquad (3)$$

where Φ is the hydraulic pressure gradient and is analogous to the electric gradient ϵ. C_h is a constant equal to $g/8\pi$ and a, again, is the cross section of the capillary. Thus, for laminar hydraulic flow, the capillary cross section appears in the flow velocity equation whereas it does not in the equations for electroosmotic flow.

---

[1]Derivation of Eq. 1, which can be found in any standard text on Physical Chemistry (Glasstone, 1952) is based on the assumption that the capillary diameter is large relative to the thickness of the double layer.

[2]See Appendix II.

The significance of capillary size independence is illustrated by consideration of the nature of a sewage sludge cake which, in general, behaves as a compressible filter medium, i.e., the cross sectional area of the capillaries within the cake decreases under filtration pressure, and hydraulic flow through the cake diminishes in time. Thus, the ultimate hydraulic dewatering capability is limited by the driving pressure and by the physical nature of the sludge. However, because electroosmotic flow velocity is independent of cross section, flow remains essentially constant regardless of the compressed state of the cake. No filter-aid chemicals are required, and electroosmosis will occur, in principle, even in gelled cakes that ordinarily might be impossible to handle with pressure filtration.

A search of the literature has yielded two attempted applications of electroosmosis to waste sludge treatment. In 1943, Beaudoin (1943) reported some success in decreasing water content in flocculated activated sludges by combining electroosmosis with rotary filtration. Somewhat later, electroosmosis was investigated (Cooling, 1952) as a method for accelerating water drainage from sewage sludge drying beds. As a result of the 1952 effort, sludge solids were increased from about 5 to 60% over a period of 21 days. With air drying and gravity drainage, sludge beds serving as controls dried to the extent of only 21% solids in the same time period. However, in the configurations of both investigations, i.e., as a technique supplementary to a prime dewatering method, electroosmosis appeared uneconomical. Thus, it was the purpose of the program reported here to investigate the phenomenon as an independent unit process in the treatment of sewage.

EXPERIMENTAL PROGRAM

The laboratory program that has been underway has been directed toward several objectives. First, an investigation of electroosmotic flow patterns in sewage sludge suspensions was carried out to determine equipment configurations for efficient solids removal. Secondly, efforts were made to identify parameters critical to efficient electroosmotic pumping under varying conditions of applied voltage and current flow. In addition, two prototype electroosmotic pumps were designed and tested, and a search for economical oxidation resistant electrodes was carried out.

As supplementary objectives, accelerated dewatering by adjustment of the surface properties of sludge suspensions with additions of surface active agents was investigated, and attempts were made to achieve more rapid dewatering by means of filtering media through which fast electroosmotic flow might be effected. However, little success was achieved in increasing flowrates with these methods, and the supplementary aspects of the program were not pursued[3].

In the following discussion, the results of the main experimental program are presented. As will be seen, the technique selected for removing solids from electroosmotically dewatered suspensions was critical for efficient pumping operation. In addition, although elevated driving voltages resulted in accelerated water flow, they decreased the electrical efficiency of electroosmosis. Furthermore, the energy requirements for dewatering were found to depend on the amount of bulk water in the sludge, all sludges behaving similarily in energy consumption up to a specific solids level apparently characteristic of the sludge type. Of two prototype electroosmotic pumps tested, one in the configuration of an inclined plane was able to efficiently dewater waste sludges to solids levels that would auto-incinerate. And,finally, two relatively inexpensive materials, magnetite and stannic oxide, were found to be useful for anode application.

SLUDGE COLLECTION AND WATER FLOW PATTERNS

Determination of electroosmotic water flow patterns allowed an assessment to be made of the most efficient method for removing solids from sludge suspensions. The technique for obtaining flow patterns was based on Eq. 1, which indicates that flow velocity is proportional to applied voltage. Thus, flux pattern analysis could be achieved by measuring potential differences between a fixed anode and a probe

---

[3] A discussion of these experiments is presented in Appendix II.

electrode as a function of probe position in an experimental cell. From such measurements, lines of equipotential could be constructed for varying cell or electrode geometries, and potential gradients could be determined throughout. Since, from Eq. 1, water flux in any area of the cell would be directly proportional to the gradient of the potential in that area, a semi-quantitative assessment of flux patterns could be extracted from the equipotential lines. The direction of water flow would, of course, depend on the sign of the zeta potential. However, for all the suspensions used in this study, water was found to move toward the cathode, indicating that the solids carried negative surface charges.

An open top plexiglass cell of approximately 500 cc capacity was used for pattern analysis (Fig. 1). The cell is composed of two chambers separated by a fine mesh stainless steel screen cathode. One chamber of the cell served to collect effluent from the other chamber in which the sludge to be dewatered was placed. The open top of the cell allowed the position and geometry of an anode to be varied with respect to the screen cathode. Platinum, platinized-titanium, and graphite were used as anode materials to minimize corrosion from anodic oxidation. Potential measurements were made with a platinum tipped probe electrode.

Typical equipotential maps are illustrated in Fig. 2. The maps shown are for samples of anaerobically digested sludge from the Los Angeles Hyperion Treatment Plant. However, they are characteristic of all the sludge suspensions examined. The equipotential lines are shown as if one were looking down into the cell at a plane located at one-half the total sludge depth. Variations in position, geometry, or the nature of the anode used did not significantly change the overall patterns that are illustrated.

Comparison of Fig. 2A, 2B, and 2C shows the most dramatic effect to be a progressive increase in potential gradient near the cathode and a decreasing gradient near the anode with continued electroosmotic pumping. This was found to be generally associated with the formation of an increasingly thick, dense cathode cake (20 wt. % solids[4]) No significant anode cake formed, despite the electrophoretic drift toward the anode that one would have expected for negatively charged solids.

Accumulation of negatively charged sludge solids at the cathode could result only from mechanical drag by water moving toward the cathode. Apparently, a sludge cake, formed at the cathode surface when the cell is filled, results in an initial elevated potential

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[4]The cake was also self-filtering, yielding relatively clear effluent with a very low level of suspended fine solids.

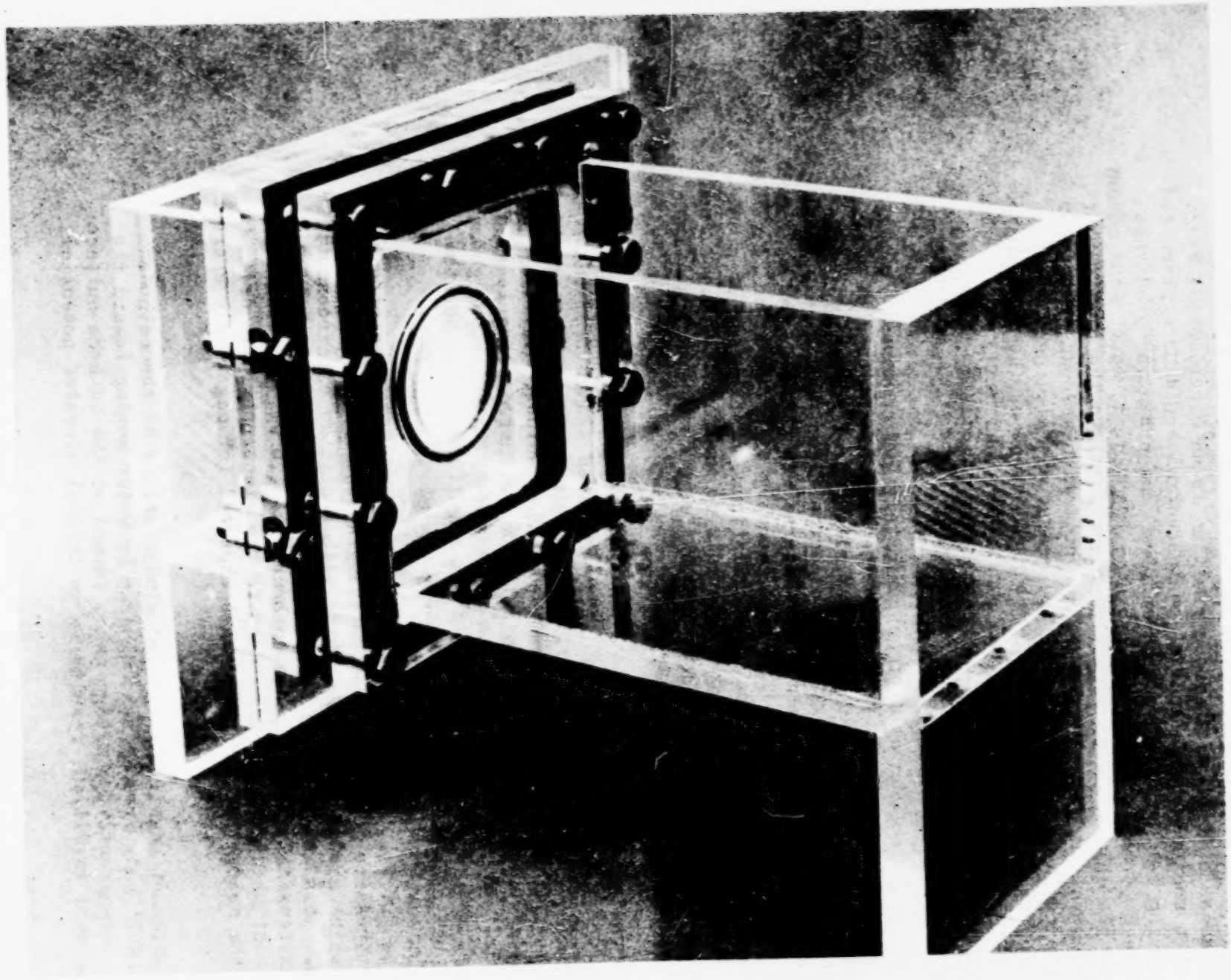

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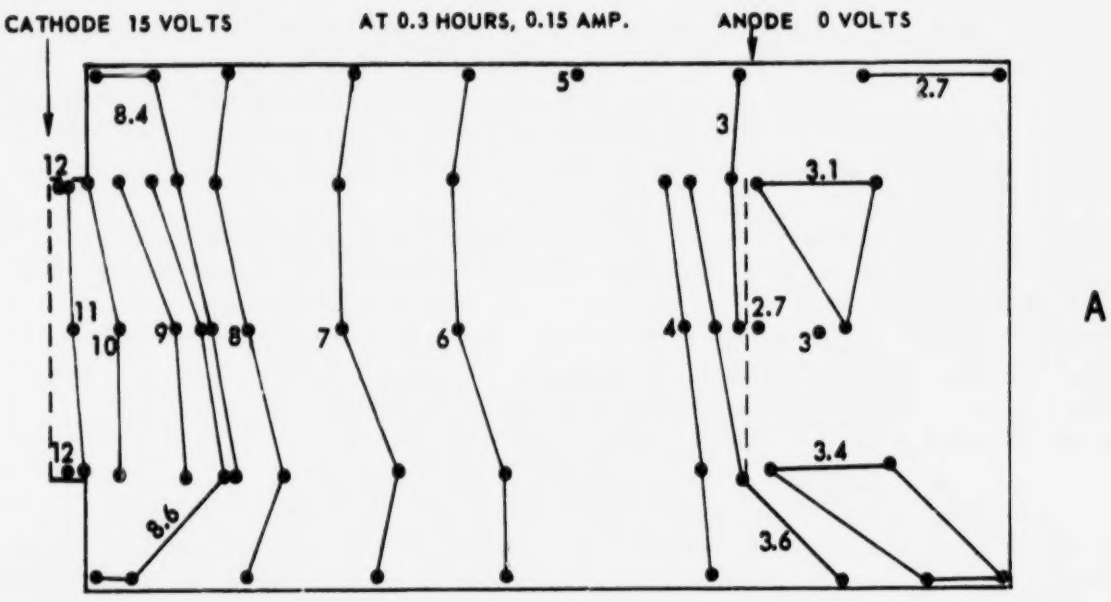
Figure 1. Open-Top Plexiglass Test Cell



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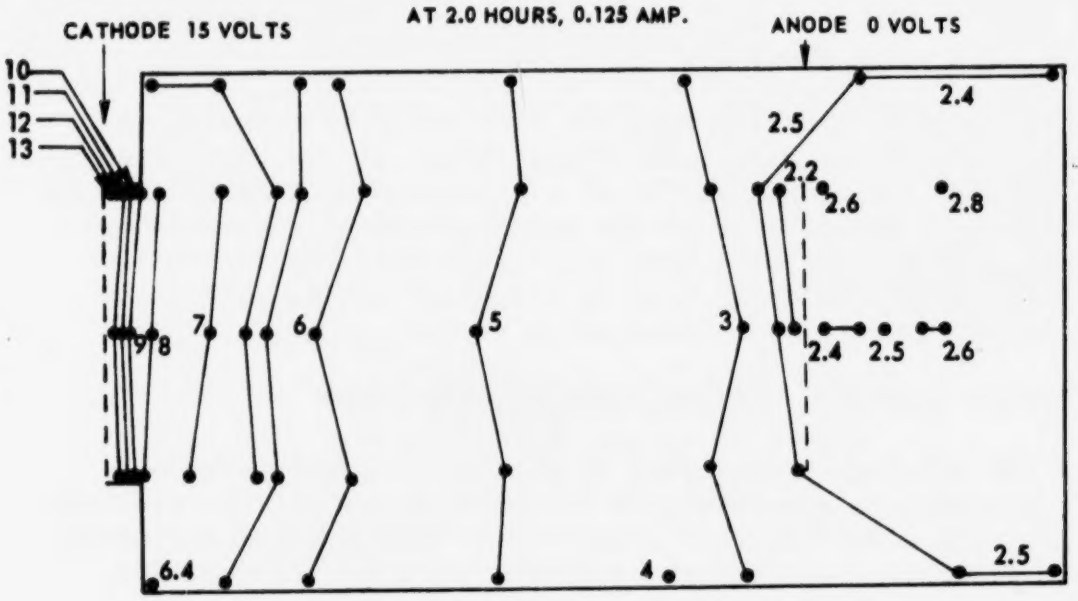

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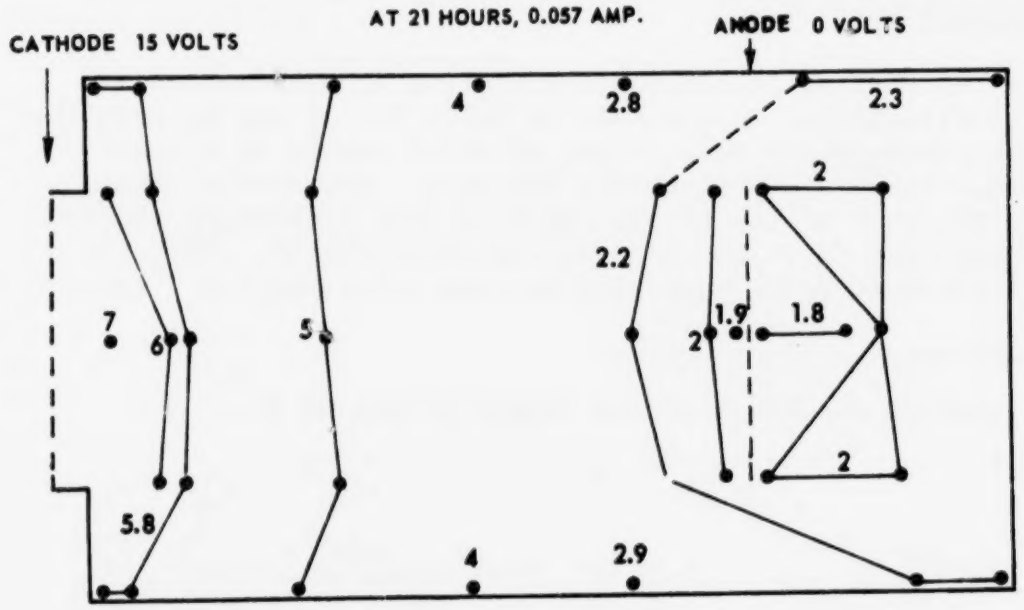

C

Figure 2. Equipotential Maps

gradient relative to the bulk of the sludge and a higher electroosmotic flowrate in the neighborhood of the cathode. Water in the bulk suspension is then forced to move with the solids by gravity to replace that which has been electroosmotically pumped through the cathode screen and, in so doing, continually builds a thicker, denser cake.

In supplementary experiments, it was determined that the presence of a thin sludge cake at the cathode surface was actually required for electroosmotic water flow to start. In general, such an initial cake was formed by gravity filtration through the clean cathode screen at the outset of an experiment. With the formation of the initial cake, the sludge solids accumulated efficiently at the cathode screen.

That no significant solids accumulation occurred near the anode probably resulted because of the low potential gradient in its vicinity and because of partial neutralization of the zeta potential by hydrogen ions formed at the anode. Measurement of pH indicated that the area near the anode became acidic (pH about 2) with continued electroosmotic pumping[5].

Based on the results obtained from the flow analysis experiments and the location of the resultant sludge cakes, it was concluded that the optimum configuration for an electroosmotic pump was one in which solids were collected from the neighborhood of the cathode. Furthermore, it was concluded that electrophoretic deposition of solids at the anode could not lead to efficient solids collection in a practical electroosmotic dewatering system.

INTERELECTRODE DISTANCE, VOLTAGE, CURRENT, AND POWER

To assess the effects of variation in electrical parameters, a series of experiments was conducted in which interelectrode distance was changed, and electroosmosis measurements were carried out under conditions of controlled voltage, current, and power dissipation.

Interelectrode Distance

The effect of varying interelectrode spacing in electroosmotic pumping is illustrated by the data in Table I. It can be seen that the energy consumed per unit volume of water pumped is directly proportional to the interelectrode distance. Apparently, ohmic losses in the bulk of the sludge increase with increasing electrode spacing resulting in a loss of electrical efficiency. Thus, in a practical electroosmotic pump, the minimum interelectrode distance,

---

[5]The effluent pH was elevated and ranged around pH 11.

in keeping with reasonable sludge flow between the electrodes, would yield highest efficiency.

TABLE I. EFFECT OF ANODE-CATHODE DISTANCE ON ELECTROOSMOSIS
(5-cm Diameter Electrodes, Hyperion Digested Sludge)

Distance Anode-Cathode, cm	Applied Voltage, volts	Initial Current, amperes	Final Current, amperes				Total Water Pumped, ml
				1/4 hr	3.0 hr	5.0 hr	
12.0	15.8	0.30	0.18	0.13	0.13	0.11	149
5.0	12.1	0.30	0.12	0.090	0.082	0.070	143
1.7	7.7	0.24	0.09	0.067	0.058	0.041	100

Controlled Voltage and Current

Typical changes in pumping energy requirements as a result of varying electrical operating parameters are illustrated in Table II. Experiments A and B were carried out at constant voltage. In experiment C, current was held constant. The applied voltage in experiment B was selected to yield approximately twice the initial voltage gradient across the sludge suspension than in experiment A. It is to be noted that nearly twice as much water was pumped in experiment B as in A, in accord with Eq. 1, i.e., electroosmotic flow velocity being proportional to applied voltage.

Despite the large differences in voltage and current conditions, the average pumping efficiency for experiments B and C is seen to be similar, and nearly the same quantity of water was pumped. Apparently, pumping efficiency is independent of the operational mode. Either controlled voltage or controlled current sources may be used.

As can be seen by re-examination of the data for experiments A and B, however, the efficiency of electroosmotic pumping will depend on the level of applied voltage or the current control point selected because part of the energy consumed is used in electrode reactions and in resistive heat losses in the system. Thus, the higher the voltage-current levels, the greater will be losses not associated with moving water.

CONSTANT POWER OPERATION

Because pumping efficiency appeared to be independent of operational mode, investigation of electrical operating parameters was continued under conditions of constant power. Power was controlled with a

TABLE II

EFFECT OF CURRENT AND VOLTAGE ON ELECTROOSMOSIS

(Hyperion Digested Sludge, 2.1 cm Interelectrode Distance, 5-cm Diameter Electrodes)

Exp. No.	Applied Voltage, volts	Initial Current, amperes	Final Current, amperes	Pumping Energy Expended, watt-hr/ml				Weight Dry, grams	Percent Solids	Total Water Pumped ml
				1/4 hr	3.0 hr	5.0 hr	Average			
A	9.4	0.29	0.09	0.077	0.074	0.046	0.065	1.56	18.6	124
B	16.8	0.61	0.18	0.163	0.094	0.084	0.10	2.61	17.6	230
C	10.0-20.0	0.30	0.25	0.075	0.12	0.11	0.10	2.63	19.3	221

device in which current and voltage values were electronically multiplied and the product signal used to control the voltage output of the electroosmosis power supply. Constant power experiments were carried out in new test cells fabricated with a fixed cathode as a bottom surface and a movable anode oriented above the cathode ("over-under cells"). The anode was attached to a servo-device that maintained it in continuous contact with the sludge cake surface regardless of the height of the cake above the cathode.

The purpose of the new test cell configuration was two-fold; first, the over-under configuration provided a convenient way to establish the initial thin sludge cake required to start electroosmotic pumping and second, the servo-device maintained the anode in contact with the sludge cake regardless of the amount of shrinkage the cake might suffer as a result of dewatering.

Sewage Sludges

With these cells, and starting with well-digested anaerobic sludges of about 2-3% solids, sludge cake accumulated at the cathode surface beneath the liquid level of the sludge suspension with maximum achievable solids content of 20%. Apparently, a steady-state flow of water from the liquid portion of the sludge suspension through the accumulated cake was established. If the liquid suspension above the cake was removed, however, the solids content of the remaining cake could be increased beyond the 20% value. It was also determined that solids accumulation was proportional to the amount of water pumped from the cell, and that the water pumped from the digested sludge was directly proportional to the power consumption up to about 30% solids. Above 30% solids, the power requirements per unit volume of water removed increased.

The results are illustrated graphically in Fig. 3 and 4. Figure 3 represents results for a cathode cake immersed beneath a liquid sludge suspension. Figure 4 represents results for a sludge cake removed from beneath liquid sludge. Although the pumping efficiencies illustrated in the two graphs are somewhat different,[6] the accumulated water removal is seen to be essentially linearly dependent on power consumption up to a level near 30% where the power required to remove water increases. The increase in power consumption has been attributed to a transition between bulk and bound water in the sludge, the former being removed in the early linear portion of the dewatering process and the latter occurring later at a higher energy cost. Another possibility, however, may be that compression of the filter cake has reduced the pore diameter to a value low enough to preclude the applicability of Zeta potential theory described in the introduction.

[6] The difference in pumping efficiencies arises because different applied voltages were used for the two measurements.

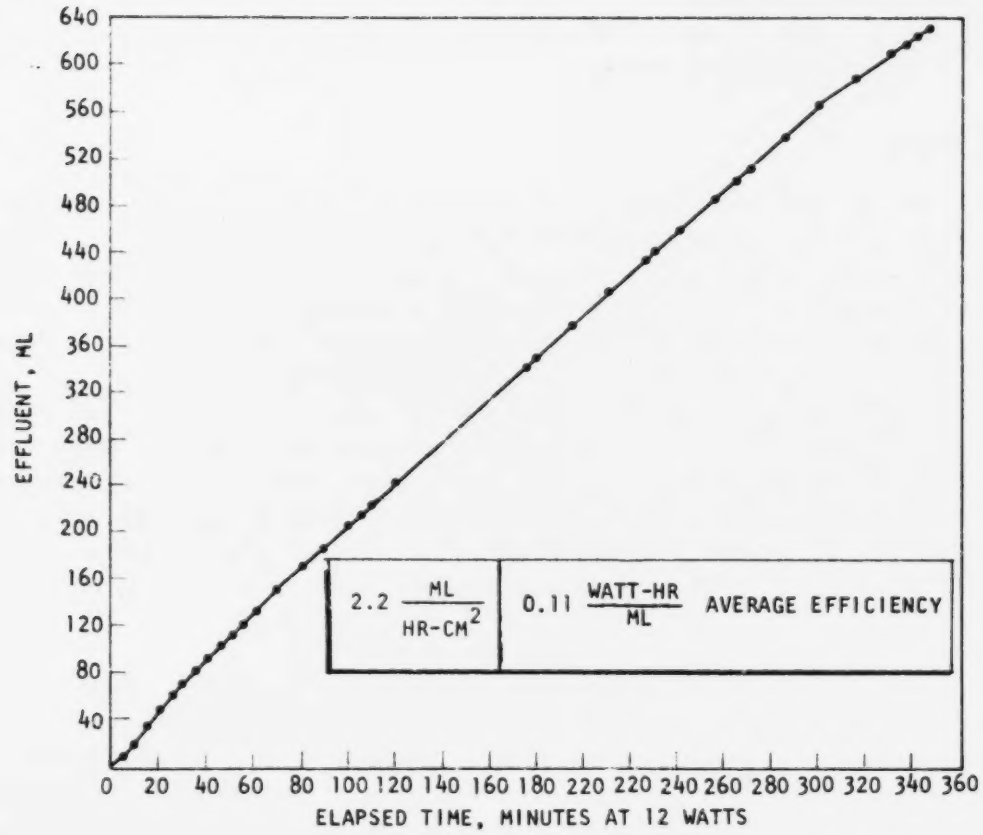

Figure 3. Relation of Water Pumped to Power Consumed (Wet)

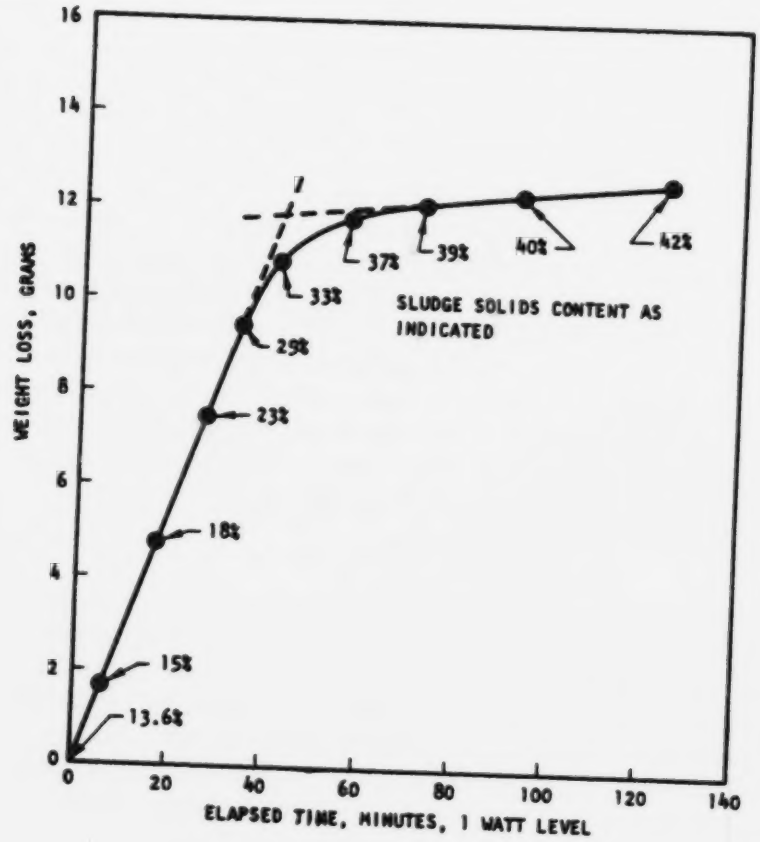

Figure 4. Relation of Water Pumped to Power Consumed (Dry)

The pattern in Fig. 4 for anaerobically treated sludge is seen, in Fig. 5, 6, and 7 to be repeated with several other sludges. However, the point at which the dewatering efficiency diminishes falls at somewhat different water content levels for each of the sludges, and the transition does not appear to be as sharp as that obtained for the anaerobically digested type. In Fig. 7, the transition point apparently had not yet been reached. These differences are believed to be caused by differences in the water binding properties of the various sludges.

In Table III, results of measurements of a series of sludges from several different sources are summarized. Included in the table are values for flowrates in ml/hr/cm^2 of electrode area and efficiencies in power consumed per unit volume of water removed for both the early linear portion of the dewatering process (the "bulk water" part) and the later, less efficient, portion of the water removal process (the "bound water" part). It is interesting to note that the electroosmotic flowrates for all the sludges are of about the same order of magnitude during the earlier portion of the process. However, after the transition, significant differences are observed in electroosmotic flowrates among the various sludges. Pumping energy requirements are also seen to be about the same, the widest variation being about a factor of two in the early part of the cycle and a factor of four at the end. Specific filter cake resistances for vacuum filtration, measured as recommended by Adrian, et al. (1968), for each of the sludges are included in the table for an indication of the difficulty one might experience in filtering these materials by conventional methods.

Perhaps the most important conclusion to be drawn from the data in Table III is that electroosmotic dewatering occurs in all the sewage sludges regardless of their processing or geographical source, i.e., successful dewatering was achieved with primary sludges, mixed activated-primary sludges, aerobic or anaerobically digested sludges, and from locations that represented extremes from industrialized areas to areas that were primarily residential. Thus, one would expect that dewatering could be accomplished by electroosmosis with any sewage sludge. It is also important to note that the flowrates and energy costs per unit volume of water removed appear to fall in about the same range for all of the materials tested, the variability being about a factor of two or three. It is expected, in view of the diversity of the sludges tested, that the same range of flowrates and energy costs per unit volume of water removed would be found for any other sludge selected for electroosmotic dewatering. Thus, it should be reasonable to extrapolate any cost estimates based on a single sludge type to any other sludge with the qualification that, ultimately, the total cost of dewatering will depend on the particular sludge's initial solids content and its fuel value.

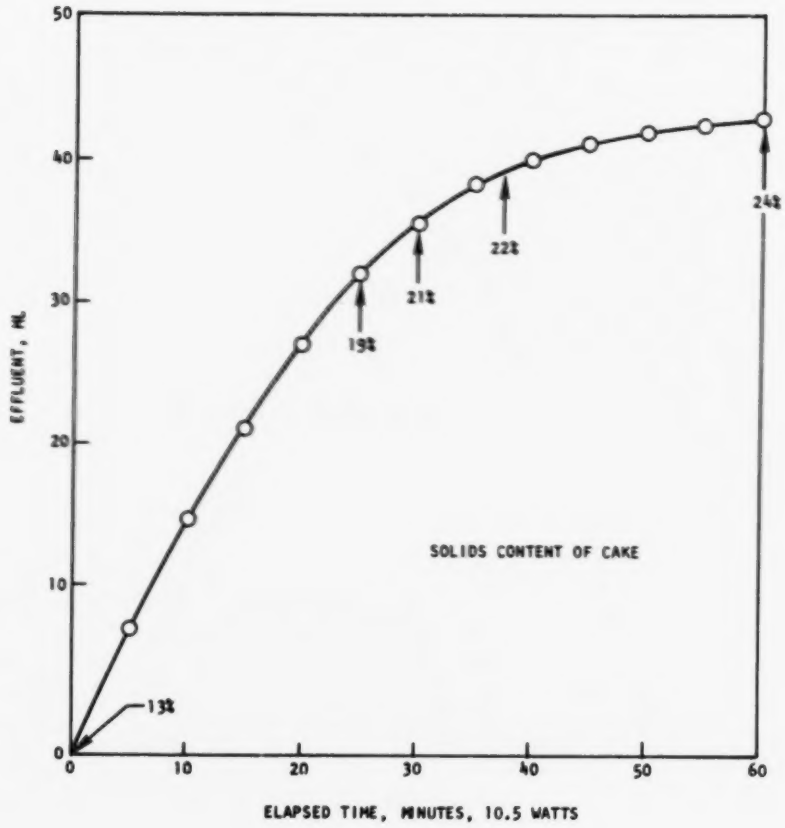

Figure 5. Electroosmosis--JWPCP Raw Sludge

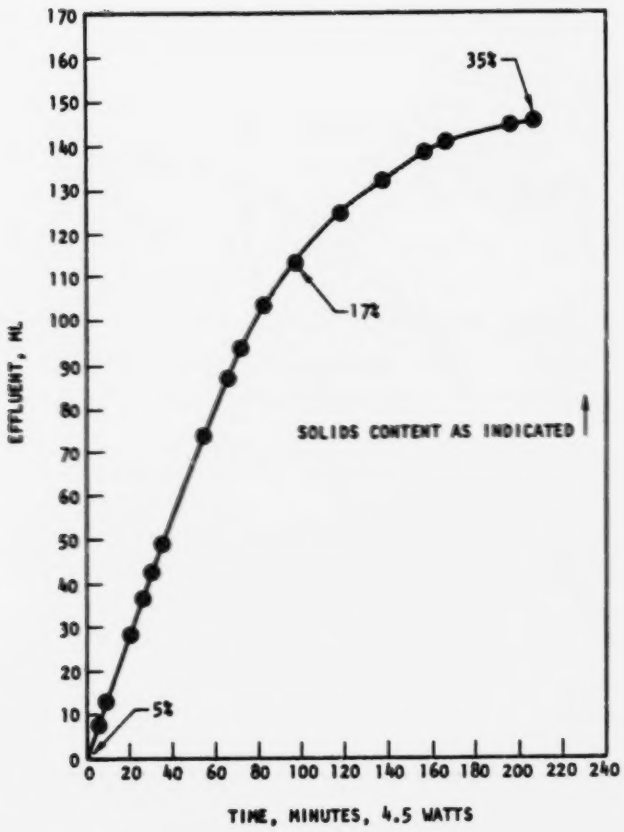

Figure 6. Electroosmosis--Aerobically Digested Sludge

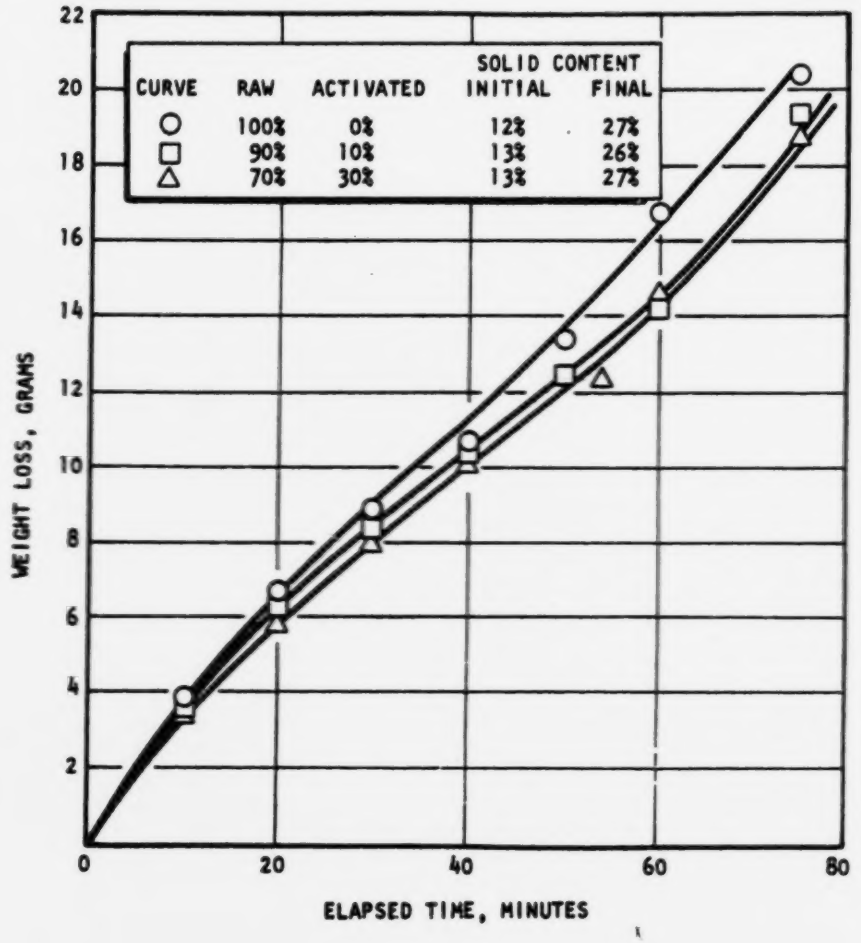

Figure 7. Electroosmosis--Hyperion Raw and Raw/Activated Sludge

TABLE III

ELECTROOSMOTIC FLOWRATES & ENERGY REQUIREMENTS

Sludge[d]	Electroosmotic Flowrates, ml/hr/cm^2				Avg. Rate	Pumping Energy watt-hr/ml			Specific Cake Resistance sec^2/gram x 10^{-10}
	Early Portion[a]		Later Portion[b]			Early Portion	Later Portion	Avg.	
	Rate	% Solids	Rate	% Solids					
Digested Hyperion	2.2	33	0.09	42	0.79	0.060	1.5	0.16	1.3
Raw Hyperion	1.4	23	0.51	25	1.3	0.14	0.38	0.15	1.3
Raw Hyperion[c]	1.4	27	-	-	1.4	0.13	-	0.13	1.7
Raw JWPCP	1.4	21	0.14	24	0.84	0.15	1.5	0.24	0.36
Raw/Activated 9:1 Hyperion[c]	1.4	26	-	-	-	0.14	-	0.14	2.5
Raw/Activated 7:3 Hyperion[c]	1.3	27	-	-	-	0.14	-	0.14	2.3
Aerobic Filter Cake, Tapia	1.7	22	0.56	34	-	0.12	0.36	0.16	-
Aerobic Digested, Tapia	1.4	17	0.13	35	0.82	0.063	0.65	0.10	9.5
Activated, Tapia	1.2	16	0.07	26	0.82	0.066	1.5	0.10	0.73

(a) Before transition

(b) After transition

(c) Stopped before transition reached

(d) A list of sources and sludge types used in this study is presented in Appendix I

Water Treatment Sludges

Because the disposal of alum sludges from reactor clarifiers in water treatment plants is a problem as severe as disposal of sewage sludges, it was appropriate to test the efficacy of electroosmotic dewatering for application to water treatment sludges. Samples of sludge were obtained from the Rinconada Water Treatment Plant near San Jose, California, and from the Metropolitan Water District Treatment Plant at LaVerne, California. Sludge from the Rinconada Plant is conventional reactor clarifier underflow. The sludge from the LaVerne Plant, however, results from the precipitation of backwashings from sand filters. The vacuum filtration characteristics of the two sludges are reported to be significantly different.[7]

Typical electroosmosis data are presented in Figs. 8 and 9. It is noteworthy that both sludges exhibit water removal characteristics similar to those of the sewage sludges, i.e., a nearly linear water removal-energy consumption relationship at the early stages of dewatering and a sharp increase in energy requirements in later stages of dewatering. Both sludges also exhibit lower energy expenditure per volume of water removed in the early stages of dewatering than do sewage sludges. The point at which the water becomes more difficult to remove, however, appears at a much lower solids level for the Rinconada sludges than for the LaVerne sludge, correlating with the information that the former is more difficult to vacuum filter than the latter.[7]

The quality factor for the disposal of water treatment sludges is the mechanical state of the dewatered solids, i.e., whether or not the resulting dewatered solids lend themselves to removal by shoveling and trucking. At the 10% solids level, the water treatment sludges are mud-like in consistency and could not be easily handled by shoveling. At the 19% level, however, the material is a thick, highly viscous paste which could be shoveled conveniently. It is apparent, then, based on the curves shown in Figs. 8 and 9, that the Rinconada sludge would be more expensive to dewater by electroosmosis than the back-wash sludge obtained from the LaVerne Plant.

PROTOTYPE APPARATUS

The experiments and results summarized in the foregoing discussion suggested several different configurations for an electroosmotic pump. However, time permitted investigation of only two configurations. These included a multiple disc device and an inclined plane device. Both devices incorporated the necessary provisions for carrying accumulated filter cake out from beneath the sludge suspension for final drying, and for the formation by gravity of an initial thin filter cake at the cathode surface before electroosmosis

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[7]Personal communication from the technical staff of the Eimco Corporation, Salt Lake City, Utah.

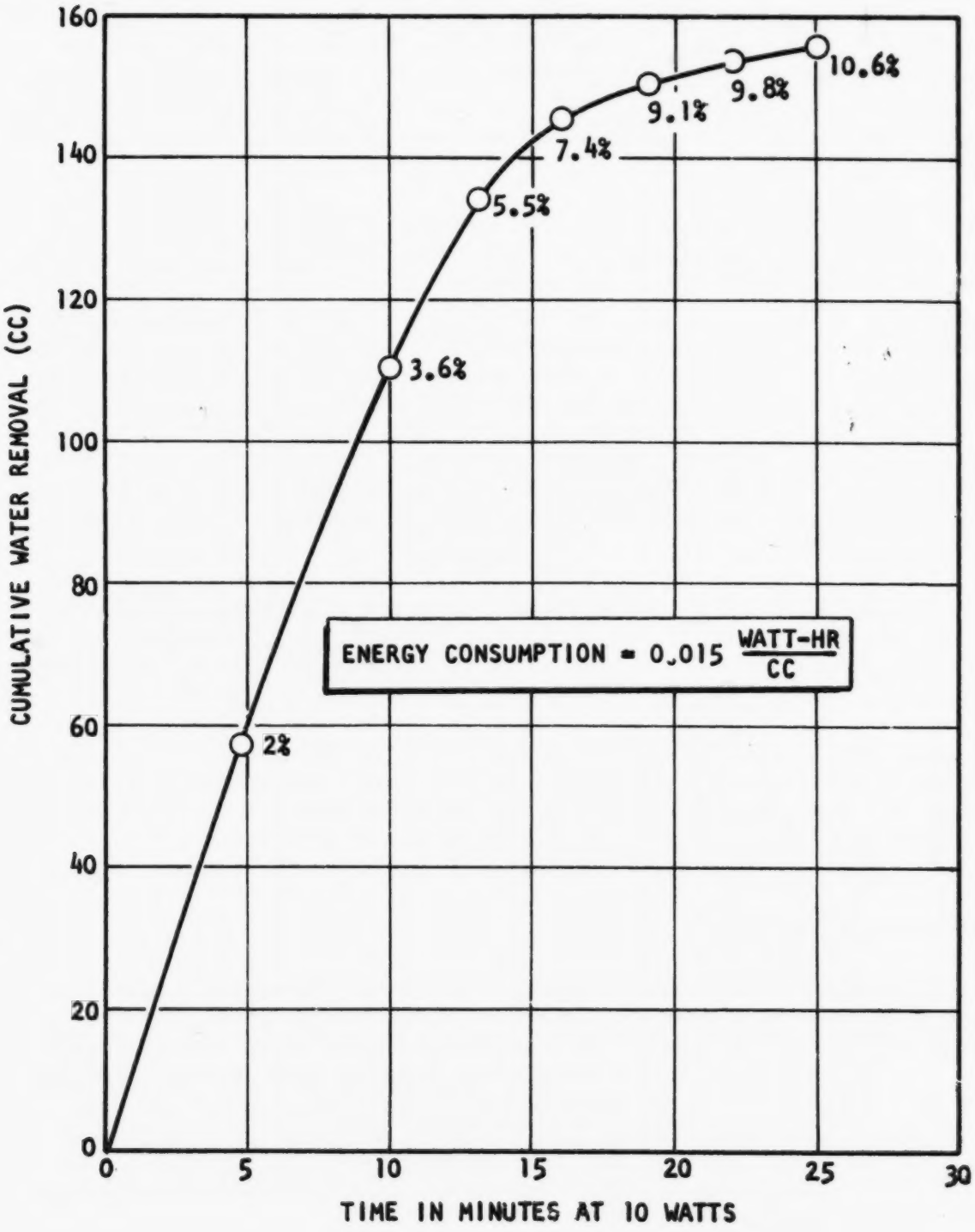

Figure 8. Rinconada Plant Alum Sludge
1.4% Suspend Solids

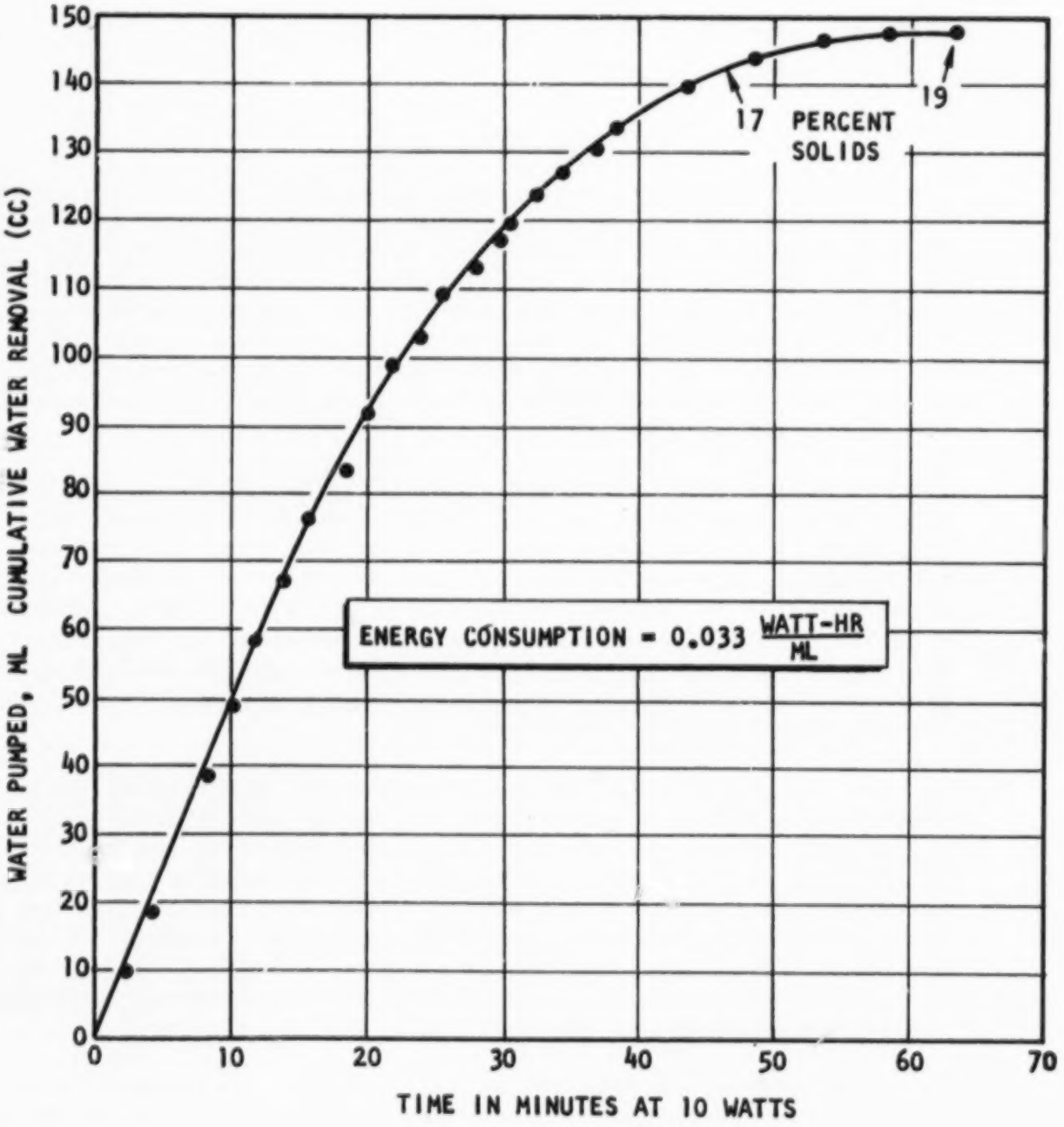

Figure 9. LaVerne Plant Alum Sludge
4.95% Suspended Solids

started. The multiple disc device provided a configuration with a large amount of electrode surface area, and, thus, a high electroosmotic volume flow could be incorporated into a small volume. The inclined plane device, as will be seen, although lower in possible electrode surface to apparatus volume ratio, provided a more convenient way to remove sludge cake from beneath the sludge suspension for final drying. Both configurations lent themselves to eventual adaptation to automatic and continuous operation. Of the two, the inclined plane device gave promise for application in an operational sewage treatment plant.

Multiple Disc Electroosmotic Pump

The model of the multiple disc electroosmotic pump is illustrated in Fig. 10. The device consists of a pair of hollow disc chambers faced with 100 mesh stainless steel screen cathodes. One disc is seen with one face removed to display the interior portion. Each chamber contains a siphon tube through which water, pumped from the sludge suspension from the outside of the chambers to the inside, can be removed. The anodes, shown removed from the model in the figure, are situated alternately between each of the chambers, facing the cathode screens.

Initial sludge cake was formed by rotating the discs through the sludge suspension while drawing vacuum through the siphon tubes. Following the formation of the initial sludge cake, electroosmosis was started. Electroosmosis was carried out at power densities of 0.25 watts/cm^2 of immersed cathode area (about 450 cm^2). Continuous rotation of the discs allowed sludge accumulating on the faces of the discs to be carried out from beneath the sludge suspension for final drying by warm air circulation. The dried cake could then be scraped from the cathode surfaces.

Several serious problems were encountered in operation of the model multiple disc electroosmotic pump. Although solids accumulated efficiently on the cathode surfaces, they tended to adhere badly, falling off and back into the sludge suspension before final drying could be achieved. Warm air drying resulted in the evaporation of water from the cathode surfaces with concurrent formation of carbonate scale. The scale then inhibited water transport through the cathode screens. In addition, the effluent water always contained a high concentration of solids.

Very high energy was required to move water, in comparison to experience with the simple electroosmosis cells described in the previous section of this report. For example, in the simple cells, electrical consumption ranged between 0.05 and 0.15 watt-hr/ml of water pumped, in contrast to values ranging between 0.25 to 1.0 found for the disc device.

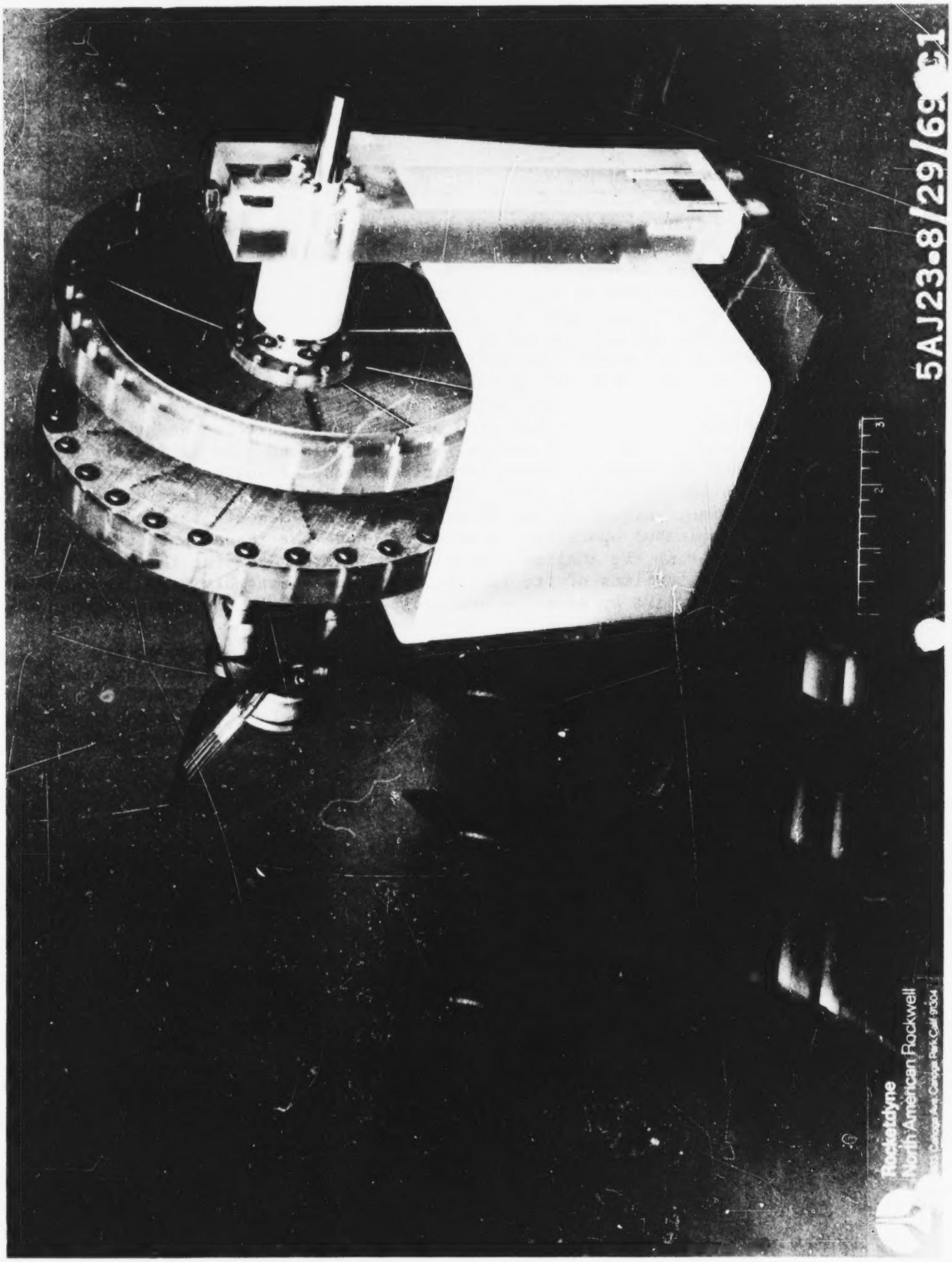

FIGURE 10. MULTIPLE DISC ELECTROOSMOTIC PUMP

Because of the difficulties encountered in operation of the model multiple disc electroosmotic pump, effort on it was terminated and redirected to the inclined plane device which showed considerably more promise in preliminary testing.

Inclined Plane Electroosmotic Pump

A photograph and drawing of the apparatus are shown in Figs. 11 and 12. The device was designed to dewater sludge from levels of about 2% solids to over 30%. As was pointed out earlier, pumping is directly related to power consumption. Thus, the constant power supply described before was used as the energy source for the unit. As can be seen, the cathode screen is oriented as an inclined plane. The screen is 50-mesh stainless steel. A platinized titanium anode and scraper assembly are carried above the cathode screen by a carriage which can move the assembly up the incline. As the anode assembly moves, sludge is accumulated between the electrodes and thickened to a level of about 15% solids. The accumulated cake is finally carried above the liquid level of the sludge suspension where it is dried to a solids content of about 30% and collected at the terminus of the incline. Liquid is collected in the trays beneath the incline. In a continuous operation, a group of anode carriages would follow one another up the incline sequentially. After dropping the solid cake at the terminus of the incline, each anode assembly would be returned to the start by conveyor and dropped again into the sludge suspension.

Because the sludge cake shrinks as it dries, it was necessary that the anode follow the decrease in cake dimensions to maintain electrical contact. Therefore, the motor controller described earlier was used to activate the anode assembly and lower the anode to maintain proper electrical contact. As will be seen, a great deal of success was achieved with the Inclined Plane device.

DEWATERING IN THE INCLINED PLANE APPARATUS

Dewatering tests were carried out in the prototype apparatus with several different sludges including digested and activated sludges from the Los Angeles Hyperion Treatment Plant and digested sludge from the Los Angeles County Treatment Plant. The digested sludges ranged between 2 and 3% in solids content and were virtually impossible to filter or settle. The activated sludge was roughly 0.6% in solids content and settled and filtered significantly more easily than the digested sludge. Successful dewatering tests were also carried out with sludges pre-concentrated to high solids levels.

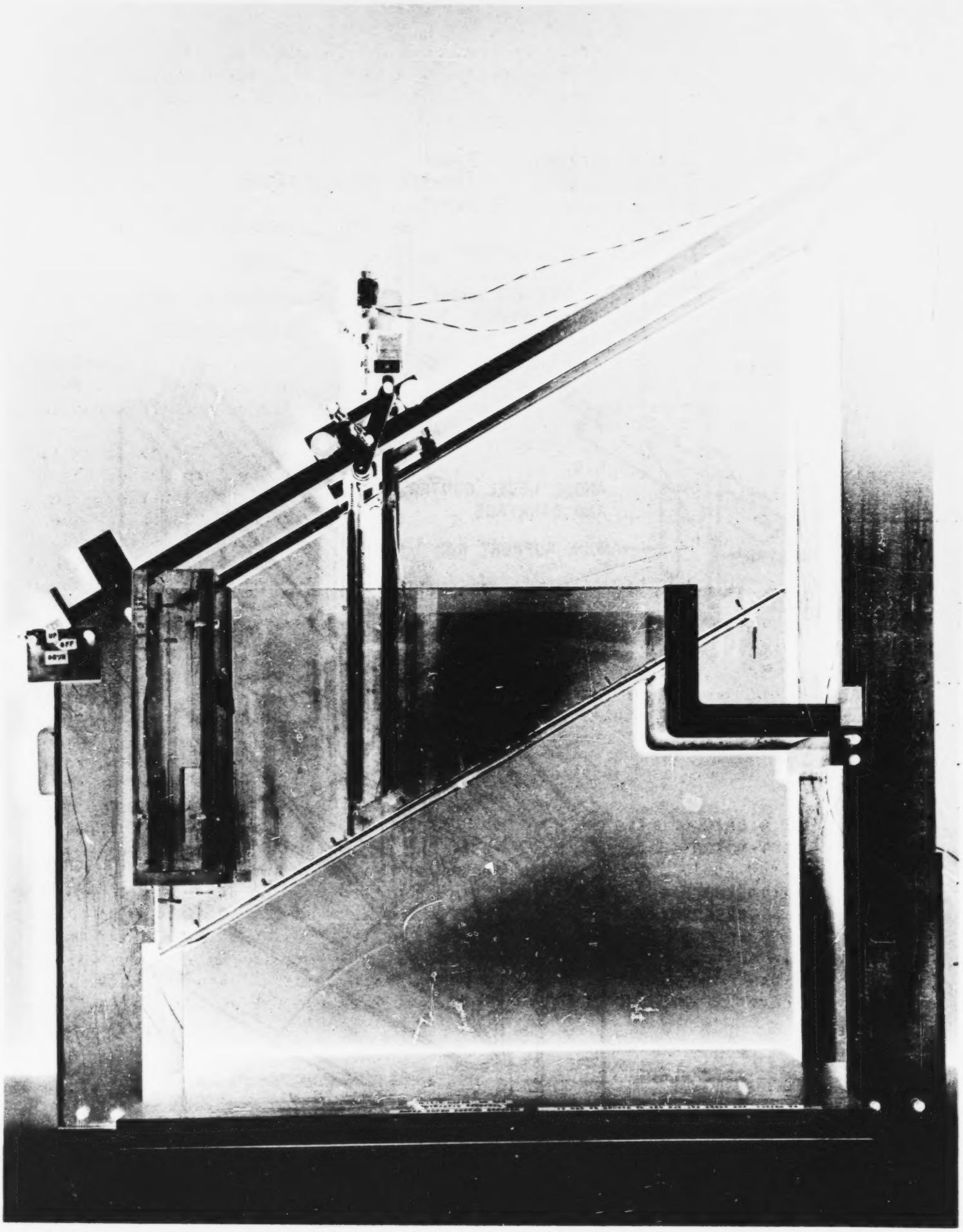

Figure 11. Prototype Apparatus

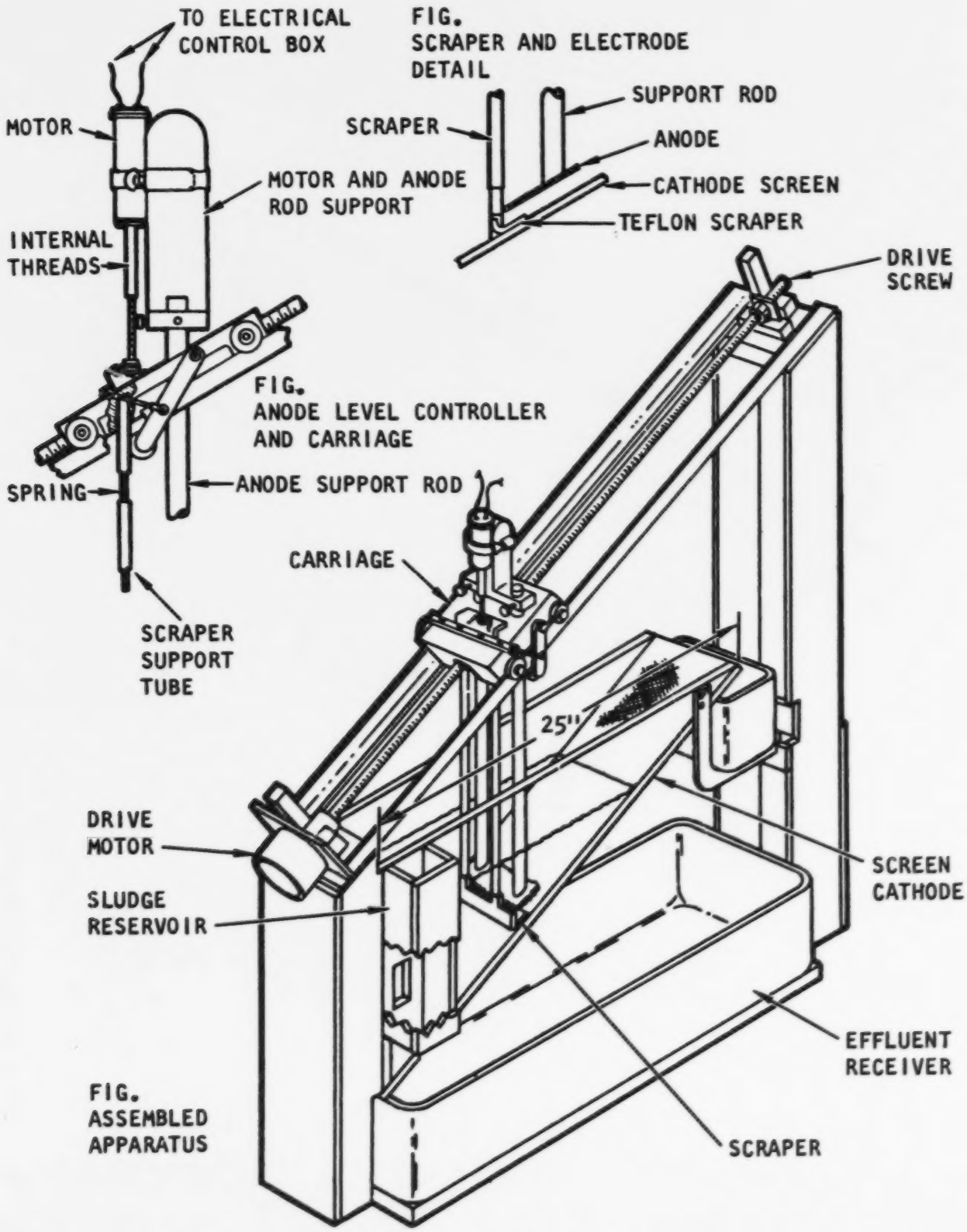

Figure 12. Schematic of Prototype Electroosmotic Pump

Wet Sludges

Typical results with wet sludges, reported in Table IV, indicate higher total water flow than those achieved in the over-under cell discussed earlier. The higher water flowrates appear to result from a very large cathode screen area in this apparatus compared to the actual active cathode area which lies directly under the anode (50 cm^2). Thus, gravity filtration, which is normally a small percentage of electroosmotic flow, became more significant.

Values for gravity flow were estimated by measurement of water flow at zero voltage in the apparatus, and the corrected values for electroosmotic flow are presented in column 6 of Table IV. In an actual installation with this type of apparatus, many anodes would be used. Thus, the ratio of active cathode area to inactive area would be large, and gravity flow would be of minor significance.

As can be seen, electroosmotic pumping yielded sludge cakes of over 30% solids with the digested sludges and cakes of about 15% with the activated sludge. No explanation is yet available for the difficulty in dewatering the activated sludge, which was also observed in the over-under cells discussed earlier. It may be that a considerably greater concentration of bound water is present in activated sludge. It should be noted that calculations of fuel values indicate that the solids levels of the digested sludges are sufficiently high to support auto-incineration, and that it is unlikely that activated sludge itself would ever be subjected to incineration without blending with primary sludge.

Except for the activated sludge, the pumping efficiencies observed for measurements in the prototype apparatus are comparable to those obtained in the small over-under cells discussed before. Activated sludges were found to be fairly easy to gravity filter and tended to pass through the 50-mesh screen cathode of the prototype pump very easily. Thus, the value for the activated sludge is thought to be in error as a result of fast gravity filtration through the inactive part of the cathode (note that the correction for gravity filtration is nearly 50% of the total flow).

It is thought that this consistency in pumping efficiency values for electroosmotic pumping, in both this apparatus and in the smaller over-under cells, is an indication that order of magnitude improvements in energy costs for electroosmotic pumping will probably not be attainable.

TABLE IV

RESULTS OF SLUDGE DEWATERING BY ELECTROOSMOSIS

IN PROTOTYPE SLUDGE DEWATERING APPARATUS

(Hyperion Sludges, Anode Area 50 cm^2, Starting Anode to Cathode Spacing, 2.0 cm)

Sludge Source	Initial Suspended Solids Content	Sludge Cake Dry Solids Percent	Power Level, watts	Total Water Flow Rate (total), ml/hr	Corrected[c] Water Flowrate Electroosmosis, ml/hr	Pumping Energy $\frac{\text{watt hrs}}{\text{ml}}$	Anode Assembly Speed, cm/hr
Digested (Hyperion)	2.7	32	12	195	175	0.07	10.7
Digested (L.A. County)	3.0	33	12	330	185	0.07	13.2
Digested[a] (Hyperion)	2.8	29	12	139	90	0.14	10.7
Activated[a] (Hyperion)	2.0[b]	16	5	470	250	0.025	10.7

(a) A 100 mesh screen was placed over the 50-mesh cathode screen normally used.

(b) Settled from 0.6% sludge.

(c) See Text.

Pre-concentrated Sludges

As will be discussed in a later section of this report, significant cost advantages in operating an electroosmotic pump can be gained if the process is used with sludges that are relatively high in solids content. Because of these advantages, a series of experiments was conducted to determine if any of the important operating parameters of electroosmosis in the inclined plane apparatus were seriously affected when the process was carried out on pre-concentrated sludges. Tests were conducted with digested sludges, raw sludges, and mixtures of raw and activated sludge.

Digested sludge was pre-concentrated in batches by electroosmosis in a large, high-current-capacity cell. Raw and activated sludges were pre-concentrated by gravity filtration.

The results of the series are presented in Table V. Comparison with the data shown in Tables I, II, III, and IV shows that energy expenditures similar to those required for wet sludges are required for dewatering the pre-concentrated sludges. It is also noteworthy that pre-concentrated sludges could be successfully dewatered without the formation of an initial sludge film on the cathode screen surface. As with the wet sludges, energy expenditure per unit volume of water removed increased with increased power input to the pumping apparatus. The dependence is illustrated clearly in Fig. 13. As before, the increased energy used at higher power levels is attributed to increased heating in the sludge cake and to reactions underway at the electrode surfaces.

Based on the data of Table V, one can conclude that electroosmosis is capable of dewatering pre-concentrated sludges with an electrical efficiency similar to that obtained with very wet sludges.

ELECTRODE MATERIALS

It was pointed out in the foregoing discussion that the anodes used in investigating electroosmotic pumping have been, in general, made of either platinum or platinized titanium. The anodic reaction underway during electroosmosis is strongly oxidizing, and the anode must be oxidation resistant. Platinum is, of course, essentially inert to oxidation. Platinized titanium, developed for anodic service in the electrochemical manufacture of chlorine, is similarly resistant to anodic oxidation. However, both materials are too expensive for service in electroosmotic dewatering applications. Platinized titanium, for example, costs approximately $\$120/ft^2$. In order to make electroosmosis economically more attractive as a unit process in sewage treatment, more reasonably priced materials were required. Thus, a testing program was carried out in which appropriate materials were sought.

TABLE V

ELECTROOSMOTIC DEWATERING OF PRECONCENTRATED SLUDGES

Initial Solids Percent	Sludge Type	Power Level, Watts	Elapsed Time, Minutes	Final Solids Percent	Pumping Energy Watt-hr/ml
13.3	Digested	11.0	38	24.3	0.11
13.3	Digested	11.0	46	25.8	0.12
13.3	Digested	10.6	44	26.6	0.10
13.3	Digested	10.9	50	28.4	0.12
13.3	Digested	10.6	50	26.3	0.10
13.3	Digested	10.6	50	24.6	0.12
15.6	Digested	10.1	60	27.7	0.15
15.6	Digested	21.4	38	29.1	0.17
9.1	Digested	10.1	50	26.3	0.10
9.1	Digested	10.3	60	29.0	0.10
9.1	Digested	10.5	70	29.5	0.12
9.1	Digested	21.8	37	30.1	0.10
9.1	Digested	23.0	35	31.1	0.10
10.4	Digested	23.0	37	29.7	0.13
10.4	Digested	19.9	35	28.0	0.10
10.4	Digested	42.0	20	28.1	0.13
10.4	Digested	85.0	12	30.3	0.16
10.3	Digested	9.6	65	27.5	0.11
10.3	Digested	31.2	29	28.9	0.15
10.3	Digested	87.0	14	27.2	0.20
10.3	Digested	70.0	15	31.5	0.18
10.3	Digested	43.0	20	27.9	0.16
10.3	Digested	19.1	29	29.6	0.086
10.3	Digested	10.2	52	27.5	0.12
10.3	Digested	26.0	30	27.6	0.11
10.3	Digested	19.0	35	25.9	0.11
8.7	Raw	9.8	31	25.1	0.09
12.7	Raw	9.9	40	26.7	0.09
12.7	Raw	9.8	45	26.3	0.09
12.7	Raw	19.9	30	27.5	0.12
10.5	50/50 Raw-Act.	9.7	40	30.0	0.06
10.5	50/50 Raw-Act.	20.3	30	25.3	0.13
10.5	50/50 Raw-Act.	43.7	15	25.6	0.13
9.9	50/50 Raw-Act.	9.8	30	25.2	0.05
12.5	50/50 Raw-Act.	21.8	15.75	25.1	0.09
13.2	50/50 Raw-Act.	9.9	40	28.8	0.10
13.3	50/50 Raw-Act.	9.6	35	26.3	0.11
13.4	50/50 Raw-Act.	43.6	12.28	26.2	0.15
13.3	50/50 Raw-Act.	9.6	18.92	24.5	0.08
13.3	50/50 Raw-Act.	9.7	35	24.7	0.10
11.8	50/50 Raw-Act.	5.3	44	24.8	0.07

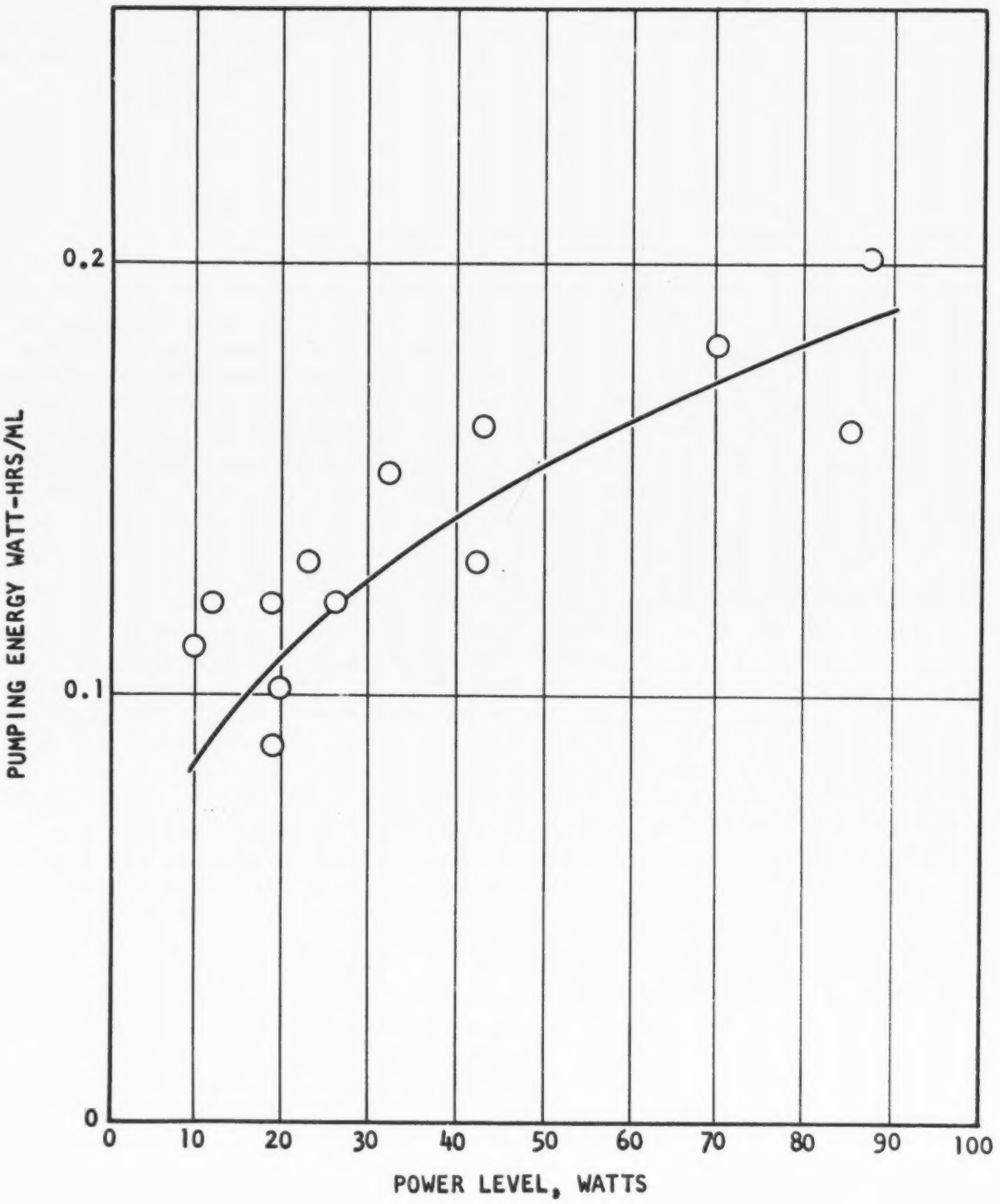

Figure 13. Pumping Energy as a Function of Power Level

Candidate anode materials were screened by subjecting them to electrochemical oxidation in digested sludge obtained from the Los Angeles Hyperion Plant. Promising materials were then selected for continued life tests.

To carry out the screening and life tests, a cell was constructed which allowed six samples to be tested in parallel and simultaneously within a single sludge reservoir. Each of the candidate materials was tested under conditions of constant current, and all the samples were tested at the same current density.

Table VI shows the results of screening tests for a variety of candidate materials. Each of the samples was subjected to a current density of 19 ma/cm^2 of surface for seven hours, except where high anodic polarization may have forced termination earlier.

As Table VI illustrates, the most promising materials for anode application, compared to platinized titanium, were magnetite and stannic oxide. The graphites and carbons all displayed relatively high anodic corrosion, and the other metals, including the flame sprayed refractories, were easily polarized, resulting in excessively high voltage drops at the anode surface. The metals and refractories apparently suffer relatively high anodic corrosion too, since the weight losses shown in Table VI for those materials resulted from short term (two to four hours) tests, compared to seven hours for the other materials.

Because of the promise displayed by stannic oxide, continued investigation of the material for anode application was carried out. Typical of most ceramics, stannic oxide varies in its properties depending upon the method selected for its preparation. Thus, the variation of type and concentration of doping materials will result in samples of variable density and electrical resistivity. Accordingly, a series of stannic oxide recipes containing doping materials known to be active sintering agents were prepared. Sample discs were pressed at 14,000 psi and sintered at 1350-1400 C for five hours. The properties of the resulting ceramic discs were then evaluated for application in anodic service. Characteristics sought included low electrical resistivity, good structural integrity, i.e., high density, and good oxidation resistance.

Some typical results for duplicate samples are illustrated in Table VII. As can be seen, the formulations containing Sb_2O_3 and ZnO display the lowest electrical resistivity and highest density combination. In continued testing, it was determined that sintering SnO_2 in an atmosphere of Sb_2O_3 consistently yielded samples with resistivities comparable to that of Sample IV. However, the presence of an additional agent like ZnO was required to obtain good structural integrity. Several other agents were found to serve as sintering aids, as is illustrated in Table VIII.

TABLE VI

ANODE TEST RESULTS

FOR HYPERION DIGESTED SLUDGES, CONSTANT CURRENT,

19 ma/cm^2 OF ANODE SURFACE-SEVEN HOUR TESTS

Sample Description	Anode Loss Grams/ Faraday	Anode Loss Moles/ Faraday	Remarks
Graphites			
Speer 8826	3.5	0.29	
Pocco AXF-5Q	3.7	0.31	
Pocco AXF-5Q	5.4	0.45	Impregnated with Halocarbon wax
Pure 4800	3.9	0.32	
UCC AGLX-58	2.8	0.23	
Rocketdyne Carbodyne	3.9	0.32	
Carbodyne-Petroleum Coke	4.7	0.39	
GE Pyrolytic	0.42	0.035	Layer separation
GE Pyrolytic	0.67	0.055	Sealed edges
Graphite Cloth	(5)		
UCC Karbate 22	2.3	0.19	
Carbons			
Vitreous	4.6	0.38	
Speer 37	11.8	1.02	
Pure 480	8.1	0.67	
Pure 4799	7.0	0.58	
UCC YBD	6.7	0.56	
Flame Sprayed on Titanium Alloy (5.7% Al, 2.5% Sn)			
TiB_2	0.14		High Anodic Polarization
TiC	0.37		
TiN	0.37		Constant current not maintained
WC	1.88		
WSi_2	0.34		Early termination
Si	0.16		
Other Metallic Samples			
Platinized Titanium	0.001	5×10^{-6}	Early termination
Ti Alloy + Pt Foil	0.43		High anodic polarization
Oxide Coated Ti Alloy	0.053		
Ti Alloy, Base	Not weighed		Constant current not maintained
Hastelloy C	18	0.26	
Niobium	17.3	0.19	
Tantalum, 10% Tungsten			(Insulating film formed)
Oxides			
SnO_2 (2% Sb_2O_3, 0.7% ZnO)	0.10	6.5×10^{-4}	Pressed @ 14K psi Sintered 5 hours 1350 C
Magnetite (Natural)	0.044	5.7×10^{-4}	

TABLE VII

STANNIC OXIDE ELECTRODES PRESSED AT

14,000 PSI, SINTERED AT 1400 C

Sample	Wt. % Sb_2O_3	Wt. % ZnO	Wt. % V_2O_5	Density, g/cc	Resistance ohms
I	0.1	-	-	3.9	3.7
II	0.1	0.7	-	6.2	200,250
III	0.1	2.0	-	6.2	150,300
IV	2.0	0.7	-	5.2	0.6, 0.7
V	2.0	2.0	-	3.5	8, 15
VI	-	-	2.0	5.5	$2x10^7$, $4x10^7$

TABLE VIII

STANNIC OXIDE COMPOSITIONS PRESSED 14,000 PSI,

SINTERED AT 1400 C, Sb_2O_3 ATMOSPHERE

Sample	Wt. % ZnO	Wt. % CdO	Wt. % Bi_2O_3	Wt. % Sb_2O_3	Density
VII	0.7	0.0	0.0	0.0	5.9
VIII	0.7	0.0	0.0	0.1	5.3
IX	0.7	0.0	0.0	0.25	4.9
X	0.0	1.1	0.0	0.0	5.2
XI	0.0	1.1	0.0	0.5	3.9
XII	0.0	0.0	3.2	0.0	4.9

Several of the formulations shown in Tables VII and VIII were selected for life testing in service. The results of the extended tests are illustrated in Table IX along with some results for natural magnetite and platinized titanium. As can be seen, the corrosion resistance of the stannic oxide formulations was found to be lower than magnetite and exceeded that of platinized titanium by a factor of only five or less. Based on the results, stannic oxide would be expected to be useful for electroosmotic pumping.

One can project an expected life for stannic oxide anodes in electroosmotic pump service from the data of Table IX. With a current density of 0.125 ma/in^2 (expected to be typical in electroosmotic pumping), a corrosion loss of about 0.01 g/Faraday (conservative, according to Table IX), and electrodes of density 30 g/in^3, about 0.01 $in/in^2/yr$ of electrode surface would corrode away. Thus electrodes a half inch thick would be expected to have about a five-year life.

TABLE IX

ANODE LIFE TESTS

HYPERION DIGESTED SLUDGE, CONSTANT CURRENT OF 19 ma/cm^2

Sample Description	Cumulative Anode Wt loss for number of hours indicated					
	grams/Faraday			moles/Faraday		
	162 hrs	325 hrs	92 hrs	162 hrs	325 hrs	92 hrs
Stannic Oxide IV	0.0072	0.0096	-	$4.8x10^{-5}$	$6.4x10^{-5}$	-
Stannic Oxide VII	0.0056	0.0088	-	$3.7x10^{-5}$	$6.2x10^{-5}$	-
Stannic Oxide VIII	0.0019	0.0028	-	$1.3x10^{-5}$	$2.2x10^{-5}$	-
Stannic Oxide X	0.0059	0.0077	-	$3.9x10^{-5}$	$6.5x10^{-5}$	-
Magnetite	-	-	0.042*	-	-	$5.4x10^{-4}$*
Platinized Titanium	0.0013	0.0023	-	$0.7x10^{-5}$	$1.2x10^{-5}$	-

ESTIMATES OF ELECTRICAL COSTS FOR ELECTROOSMOTIC PUMPING

From the results presented in the foregoing discussion, some preliminary estimates of the electrical costs of electroosmotic pumping can be made. Cost calculations can be based on the data presented in Table III and on the assumption that the weight of sludge which can be collected is equal to that contained in the volume of water removed. Thus, with an average energy consumption for the early, more efficient portion of the dewatering process being 0.11 watt-hr/cc, and assuming power cost of $0.01/kwh, one obtains the curve shown in Fig. 14. Plant costs are not included in the calculation.

It is to be noted that the estimated electrical costs for processing fall dramatically with an increase in initial sludge solids content. This cost reduction results because the cost of dewatering is determined by the amount of water that must be removed to achieve a desired cake dryness level. To dewater sludge from 2% to 30%, one must remove about twice the water than that necessary to achieve 30% sludge when starting with a 4% suspension.

Electrical costs can be seen to be attractive if some preconcentration of material to about 6-10% solids is assumed. Thus, for mixed waste-activated and primary sludges, which we have found to be gravity filterable to solids contents as high as 20%, costs for dewatering to burnable material should be dramatically lower than that of the digested sludge, which does not settle as efficiently. Since it was shown earlier that electroosmosis does, in fact, work well with preconcentrated sludges, one concludes that the process will be most attractive if applied in tandem to a pre-treatment stage that thickens the influent.

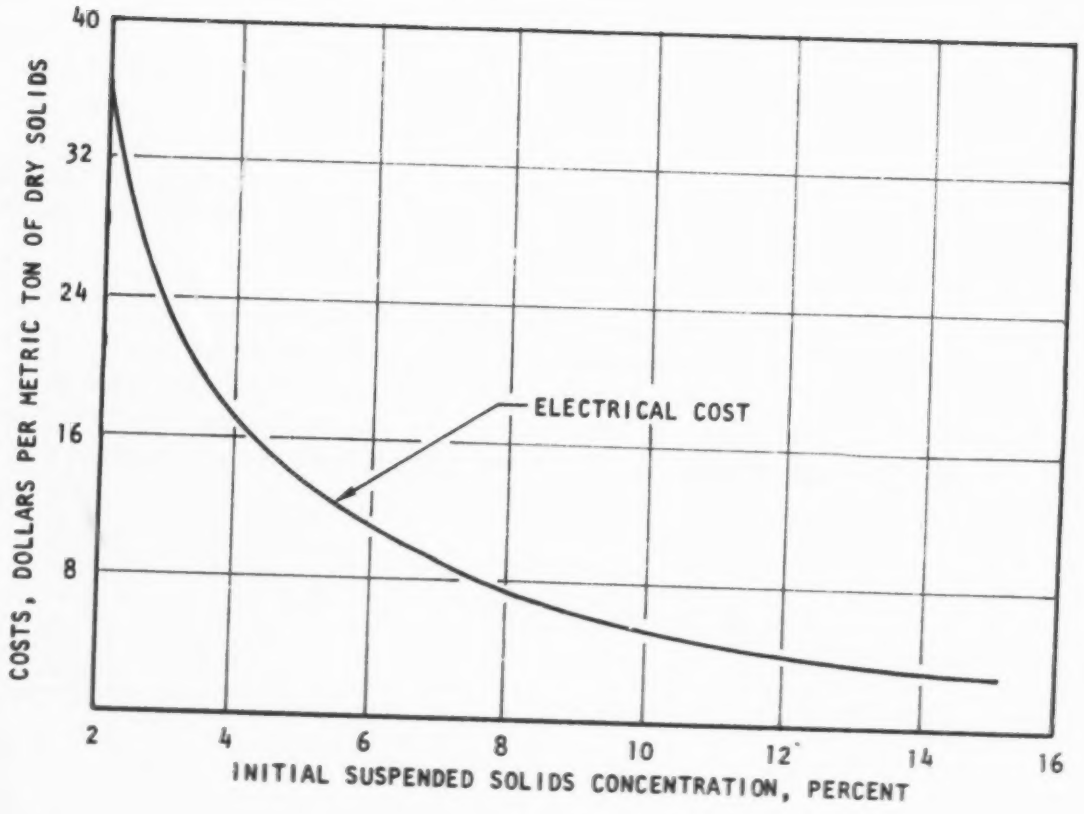

Figure 14. Electrical Costs for Electroosmotic Dewatering

ACKNOWLEDGEMENT

The work reported herein was carried out over the period 24 June 1968 through 23 July 1970 by the staff of the Rocketdyne Research division. Dr. B. L. Tuffly, Manager, Environmental Sciences and Technology, served as the Program Manager. Dr. Jerome Greyson was the Responsible Scientist. Members of the Technical Staff contributing to the program were Dr. H. H. Rogers, Dr. O. Kalman, Mr. P. Faurote, and Dr. H. Offner.

Dr. R. B. Dean, Chief, Ultimate Disposal Research Section of the Advanced Waste Treatment Research Laboratory, Federal Water Quality Administration, served as the Project Officer for the program. The Rocketdyne staff wishes to express their appreciation for the interest and cooperation provided by Dr. Dean throughout the course of this research.

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APPENDIX I

SOURCE AND TYPES OF SLUDGES TESTED FOR EFFICACY OF ELECTROOSMOTIC DEWATERING

Source	Type
Las Virgenes Water District Tapia Plant, Calabassas, California	Activated sludge Activated digested sludge Aerobic filtercake-prepared from gravity filtered with filter and Rohm and Haas C-7 polyelectrolyte
Los Angeles County Joint Water Pollution Control Plant 24501 S. Figuroa St. Harbor City, California	Raw primary sludge Anaerobically digested sludge (about 10 days)
City of Los Angeles Hyperion Treatment Plant 12000 Vista Del Mar Playa Del Rey, California	Raw primary sludge Activated sludge Anaerobically digested sludge (about 21 days)
Metropolitan Water District Water Treatment Plant LaVerne, California	Alum water treatment sludge, sand filter backwashings
Rinconada Water Treatment Plant San Jose, California	Alum water treatment sludge, reactor-clarifier underflow

APPENDIX II

ACCELERATED DEWATERING THROUGH TAILORING OF SURFACE PROPERTIES

ADJUSTMENT OF ZETA POTENTIAL TO INCREASE RATES OF ELECTROOSMOSIS

Acceleration of electroosmosis through adjustment of the zeta potential of sludge particle surfaces was investigated by measuring the electrophoretic mobility, i.e., the velocity with which a charged particle drifts through a distance of 1 cm under a potential gradient of 1 volt. Electrophoretic mobility is directly proportional to the zeta potential and is, essentially, the inverse of electroosmotic velocity. For particles of the order of 1 micron in diameter, electrophoretic mobility can be measured by direct observation with a travelling microscope, the suspension being placed in a tube of rectangular or circular cross section. For these measurements, a commercial micro-electrophoresis unit called the "Zeta Meter" was procured. The Zeta Meter consists of a binocular microscope, a micro-electrophoresis cell in which is drilled a drift tube of circular cross section, and a precision power supply.

Initial experiments were conducted to assess the extent to which variations in the pH and conductivity of the supernatant would affect the electrophoretic mobility (EM) of digested sludge obtained from the Los Angeles Hyperion Municipal Treatment Plant. Measurements were carried out with suspensions of 1 cc aliquots of sludge in 100 cc of distilled water, and pH and conductivity adjustments were made to the mixture. Buffer tablets were used for pH adjustment, and NaCl was used to adjust conductivity.

The results of the measurements are presented in Tables X and XI, and Fig. 15. In Table X, the influence of pH on EM is shown over the pH range 3 to 12. It is to be noted that at pH 3, the value of EM is zero, resulting, apparently, from the partial neutralization of the negative surface charge of the sludge by hydrogen ions. Above pH 3, the value of EM is relatively independent of the acidity of the solution. At high pH, EM increases. However, it is also to be noted that the buffer tablets increase the specific conductivity of the solutions with increases in pH. At pH 12, the conductivity decreases. Thus, the increase in EM for the pH 12 solution may result from adsorption of the buffer salts imparting a higher negative charge to the sludge particle surface.

TABLE X

ELECTROPHORETIC MOBILITY - pH

pH	Specific Conductivity x 10^6 $(ohm\text{-}cm)^{-1}$	EM Microns/Volts sec cm
3.1	2,600	0
4.1	4,400	1.1
6.8	8,200	1.1
8.0	10,000	1.1
12.0	8,000	1.5

TABLE XI

ELECTROPHORETIC MOBILITY-CONDUCTIVITY

Concentration Equivalent NaCl/Liter	$(Ionic\ Strength)^{1/2}$	Specific Conductance x 10^6 $(ohm\text{-}cm)^{-1}$	EM Microns/Volt sec cm
0.1	0.30	12,000	0.9
0.065	0.25	9,000	1.3
0.05	0.22	4,950	1.7
0.02	0.14	2,925	1.6
0.005	0.07	750	2.0
0.001	0.03	260	2.4

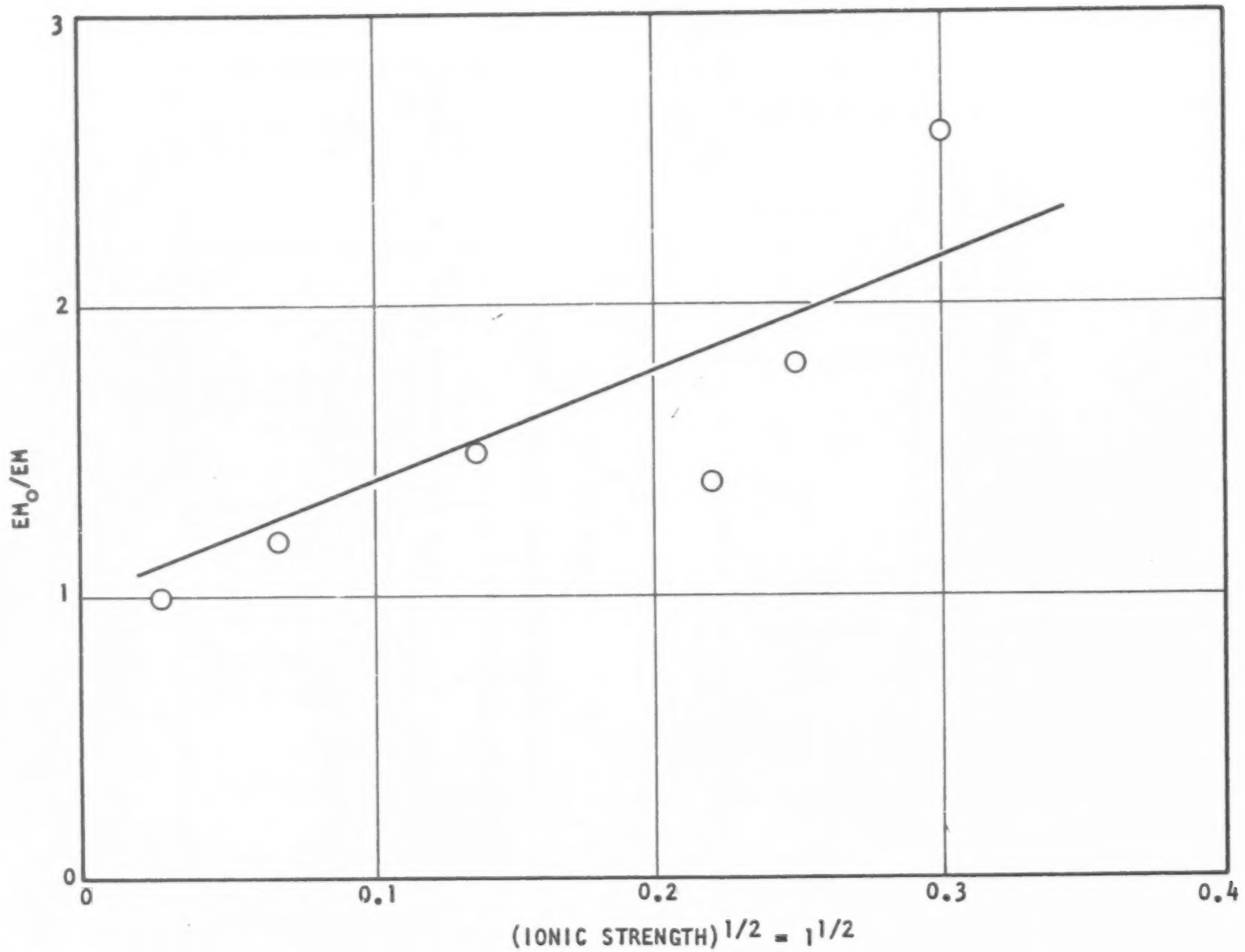


Figure 15. Electrophoretic Mobility Dependence on Ionic Strength

Values of EM as a function of conductivity are shown in Table XI. It is to be noted that EM is strongly dependent upon solution conductivity. In Fig. 15, the ratio EM_o/EM, where EM_o is the mobility at infinite dilution and EM is its value at the measured concentration, is plotted versus the square root of ionic strength. At values of $I^{1/2}$ less than about 0.15, the data follow a straight line, while at higher concentrations, the data deviate from the line. Such behavior is typical of suspensions which follow Debye-Huckel theory and is indicative of the influences of the dissolved salt on the surface charge of the sludge particles.

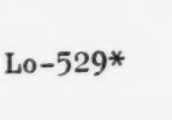
It was this influence of dissolved materials on surface charge which was to be exploited to increase the electrophoretic mobility of sludge and thus increase the electroosmotic velocity of water out of sludge. It was expected that significant variations in mobility could be effected by small additions of surface active agents or of salts with multiple negative charges. These species could adsorb to the surface of the sludge particles and impart to them an enhanced negative surface charge, thus increasing the zeta potential and the electrophoretic mobility. A series of experiments was carried out to determine whether beneficial increases in electrophoretic mobility could be obtained by additions of multivalent anionic salts and several commercial detergents.

Solid sludge was obtained from the sedimented material resulting from centrifuged (about 1 hour at 17,500 rpm) Hyperion digested sludge. The supernatant itself was collected, filtered through a 3μ Millipore filter, and again centrifuged for an hour. Measurements were carried out in supernatant, water, and ammonium bicarbonate solution (to simulate sludge supernatant). Weighed amounts of sludge solids and varying concentrations and types of surface active agents were added to the liquids. The surface active agents which were tried are listed in Table XII, and results are shown for the three suspending liquids in Tables XIII, XIV, and XV.

As can be seen, regardless of the nature or concentration of the additive tried, significant increases in electrophoretic mobility for the sludge solids were not obtained. In view of the results, it was concluded that increasing the electroosmotic flowrates of water out of sludge by adjustment of sludge zeta potential was not a promising approach and the effort was terminated.

TABLE XII

SURFACE ACTIVE AGENTS TESTED

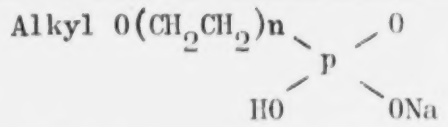
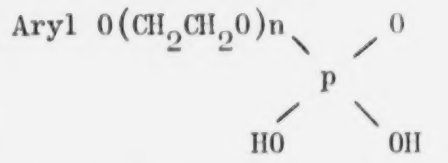
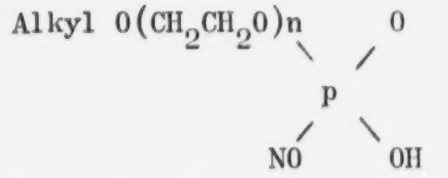
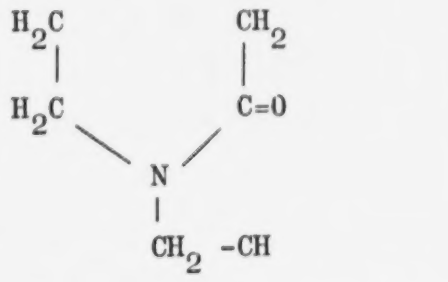
Surfactant	Chemical Formula	Type, If Organic
Alconox	A long chain alkyl sulfonate	Anionic
Calgon	$(NaPO_3)_x$	
Sodium Acid Phosphate	$Na_2HPO_4 \cdot 7H_2O$	
Potassium Sulfate	K_2SO_4	
Miracle White Super Cleaner	--	
Boric Acid	H_3BO_3	
Sodium Silicate	Na_2SiO_3	
Sodium Tetraborate	$Na_2B_4O_7$	
Sodium Citrate	$Na_3C_6H_5O_7$	
Sulfanilic Acid	$NH_2C_6H_4SO_3 \cdot H \cdot H_2O$	
Igepon T-73*	$C_{17}H_{33}\overset{\overset{O}{\|}}{C}\overset{\overset{CH_3}{\|}}{-N}-CH_2CH_2SO_3Na$	Anionic
Igepon AP-78*	$C_{17}H_{33}\overset{\overset{O}{\|}}{C}-O-CH_2CH_2SO_3Na$	Anionic
Igepon AC-78*	$C_{11,13}H_{23,27}\overset{\overset{O}{\|}}{C}-O-CH_2CH_2SO_3Na$	Anionic
Igepon Cn-42*	$C_{15}H_{31}\overset{\overset{O}{\|}}{C}\overset{\overset{C_6H_{11}}{\|}}{-N}-CH_2CH_2SO_3Na$	Anionic
Igepal CO-630*	$C_{19}H_{19}-O(CH_2CH_2O)_8CH_2CH_2OH$	Non-ionic
**Gafac Lo-529*	Aryl $O(CH_2CH_2O)n$ (C_8-C_{20}) 	Anionic

* Product of General Aniline and Film Corp., 140 W. 41st St., New York. Manufactured by Monsanto, 800 N. Lindbergh Blvd., St. Louis, Mo.

**GAFAC Surfactants are mixtures of mono and diesters; increase in product number indicates increase in n.

TABLE XII

(Concluded)

Surfactant	Chemical Formula	Type, If Organic
Gafac GB-528*		Anionic
Gafac RE-610*		Anionic
Gafac RS-710*		Anionic
Santomerse ME-b	Sodium salt of linear alkyl-arl sulfonate	Anionic
PVP ND K-30*		Viscosity alternating material

* Product of General Aniline and Film Corp., 140 W. 41st St., New York.
Manufactured by Monsanto, 800 N. Lindbergh Blvd., St. Louis, Mo.

TABLE XIII

ELECTROPHORETIC MOBILITIES IN SLUDGE SUPERNATANT

Sample	gm Solid Sludge/ 1000 ml	gm Added Material/ 1000 ml	Conductivity $ohm^{-1} cm^{-1} \times 10^3$	EM Microns/sec / Volts/cm
Supernatant + Solid	3.5	0	6.1	1.32
Supernatant + Solid + Alconox	2.4	1.23	7.2	1.89
Supernatant + Solid	2.9	0	6.8	1.51
Supernatant + Solid + $Na_2HPO_4 \cdot 7H_2O$	2.9	1.37*	6.8	1.44
Supernatant + Solid	1.1	9	6.7	1.52
Supernatant + Solid + K_2SO_4	1.1	1.2	8.2	1.30
Supernatant + Solid	3.6	0	6.8	1.39
Supernatant + Solid + Alconox	3.6	.127*	6.7	1.52

*1 ml of concentrated solution in water added.

TABLE XIV

ELECTROPHORETIC MOBILITIES IN WATER

Sample	gm Solid Sludge 1000 ml	gm Added Material/ 1000 ml	Conductivity $ohm^{-1} cm^{-1} \times 10^3$	EM Microns/sec / Volts/cm
Water + Solid	3.5	0	6.8×10^{-2}	1.84
Water + Solid + Alconox	3.6	1.76	1.6	2.57
Water + Solid	3.0	0	5.0×10^{-2}	1.89
Water + Solid + $Na_2HPO_4 \cdot 7H_2O$	3.0	1.36	1.8	1.91
Water + Solid	2.6	0	5.4×10^{-2}	1.48
Water + Solid + K_2SO_4	2.6	1.43	1.95	1.74

TABLE XV

ELECTROPHORETIC MOBILITIES IN NH_4HCO_3 SOLUTION (2600 ppm)

Sample	gm Solid Sludge 1000 ml	gm Added Material/ 1000 ml	Conductivity $ohm^{-1} cm^{-1} \times 10^3$	EM $\frac{Microns}{sec} / \frac{Volts}{cm}$
Solid	2.6	0	3.0	1.40
Solid + Calgon*	2.6	.083	2.8	1.48
Solid + Calgon*	2.6	.42	2.8	1.49
Solid	2.4	0	3.2	1.44
Solid + Calgon	2.4	.27	3.4	1.52
Solid	3.2	0	3.0	1.47
Solid + Alconox	3.2	.128	3.0	1.64
Solid	1.4	0	2.9	1.57
Solid + Alconox	1.4	.380	2.9	1.55
Solid	2.9	0	3.1	1.60
Solid + Alconox	2.9	.767	3.8	2.01
Solid	2.3	0	3.0	1.28
Solid + Miracle White Super Cleaner*	2.3	.107	3.0	1.22
Solid + Miracle White Super Cleaner*	2.3	.457	2.5	1.41
Solid + Miracle White Super Cleaner*	2.3	.800	2.4	1.57
Solid + Miracle White Super Cleaner*	2.3	1.77	3.1	1.49
Solid + Miracle White Super Cleaner*	2.3	5.30	3.4	1.49
Solid	1.0	0	3.2	1.43
Solid + H_3BO_3	1.0	1.51	3.2	1.47
Solid	.95	0	3.1	1.51
Solid + $Na_2B_4O_7$	.95	1.34	3.2	1.56
Solid	.62	0	3.1	1.48
Solid + Na_2SiO_3	.62	1.7	3.1	1.47
Solid	1.3	0	3.2	1.53
Solid + $NH_2C_6H_4SO_3 \cdot H \cdot H_2O$	1.3	1.6	3.2	1.46

* Material dissolved in water prior to adding to sludge suspension

TABLE XV

(Concluded)

Sample	gm Solid Sludge 1000 ml	gm Added Material/ 1000 ml	Conductivity $ohm^{-1}cm^{-1} \times 10^3$	EM Microns/Volts sec cm
Solid	2.8	0	3.1	1.65
Solid + Na_3 Citrate	2.8	.123	3.1	1.27
Solid	1.1	0	3.1	1.43
Solid + Na_3 Citrate	1.1	2.4	4.8	1.63
Solid	1.5	0	3.0	1.35
Solid + IGEPON T-73	1.5	1.6	4.5	1.59
Solid	1.3	0	2.9	1.40
Solid + IGEPAL CO-630	1.3	2.5	2.9	1.57
Solid	1.3	0	2.9	1.40
Solid + GAFAC LO-529	1.3	2.8	2.8	1.74
Solid	.91	0	3.0	1.29
Solid + GAFAC RE-610	.91	4.5	2.7	1.52
Solid	2.1	0	2.8	1.41
Solid + GAFAC RS-710	2.1	2.0	2.8	1.68
Solid	1.0	0	2.8	1.29
Solid + IGEPON AP-78	1.0	2.5	3.6	1.69
Solid	3.9	0	3.1	1.25
Solid + IGEPON CN-42	3.9	3.9	3.7	1.51
Solid	3.7	0	3.5	1.35
Solid + GAFAC GB-520*	3.7	1.5	2.9	1.47
Solid	2.1	0	3.1	1.67
Solid + PVP Type ND K-30	2.1	2.8	2.9	1.39
Solid	3.7	0	3.1	1.37
Solid + IGEPON AC-78	3.7	2.6	3.0	1.51
Solid	2.8	0	3.1	1.27
Solid + SANTOMERSE ME-b	2.8	2.4	3.0	1.69

* Diluted to 40 ml

ACCELERATING ELECTROOSMOSIS THROUGH SELECTED FILTERING MEDIA

An alternative to adjusting the zeta potential of sludge is the selection of a suitable filtering medium with an intrinsic zeta potential greater than that of the sludge itself. The potential gradient giving rise to electroosmosis could then be applied across the filter medium rather than the sludge suspension. Because of the elevated zeta potential in the filter medium, electroosmotic flow velocity would be expected to be greater through it than could be achieved with identical voltage gradients across the sludge suspension. Such a configuration would be, in essence, an electro-filter, with the driving force for filtration being an electrical gradient rather than a hydraulic gradient as is used in ordinary filtration.

The apparatus used for investigating the efficacy of electroosmotic pumping through supplementary filtering media is shown in Fig. 16. It consists of a glass cell of approximately 200-cc capacity. The cell is divided into an effluent and sludge chamber. At the facing ends of the chambers, pyrex O-ring flanges have been sealed (Sargent Catalog No. S-40223). The cell chambers can thus be separated conviently by screen electrodes or sandwiches of membranes and screen electrodes. The effluent chamber contains a liquid leveling tube to preclude gravity filtration, and the sludge chamber is fitted with a stirring shaft which passes through the end opposite the O-ring flange. The stirring shaft serves also as an anode and its effective position relative to the screen cathode or sandwich can be adjusted.

Provision was made in the cell to pump sludge through the sludge chamber while withdrawing effluent from the effluent chamber. Pumping from a volume of sludge, large relative to the total effluent withdrawn, allowed one to carry out measurements of electroosmotic flow out of the sludge under conditions of constant solids content.

The rotating anode was located about 1 cm from the membrane surface in the measurements discussed here. In most runs, a spiral stainless-steel wire cathode was used and this was kept almost in contact with the membrane (Fig. 17). Use of the wire electrode provided free circulation of liquid near the cathode and ready removal of gas bubbles. In control runs, stainless-steel screen (approximately 50 mesh) was clamped between the O-ring joints and served both as the cathode and as a base for the accumulation of a sludge "membrane". The purpose of the latter was to provide a comparison in flowrates between sludge itself and the filtering media.

In Table XVI, the data obtained for a variety of membranes and filtering media are presented. The column headings in the table, i.e., electroosmotic permeabilities, k_e, specific resistances, R, and other parameters were derived from the equations

$$Q = k_e A(v/d) \qquad \text{II-1}$$

$$I = (\ell/R)\ (v/d) \qquad \text{II-2}$$

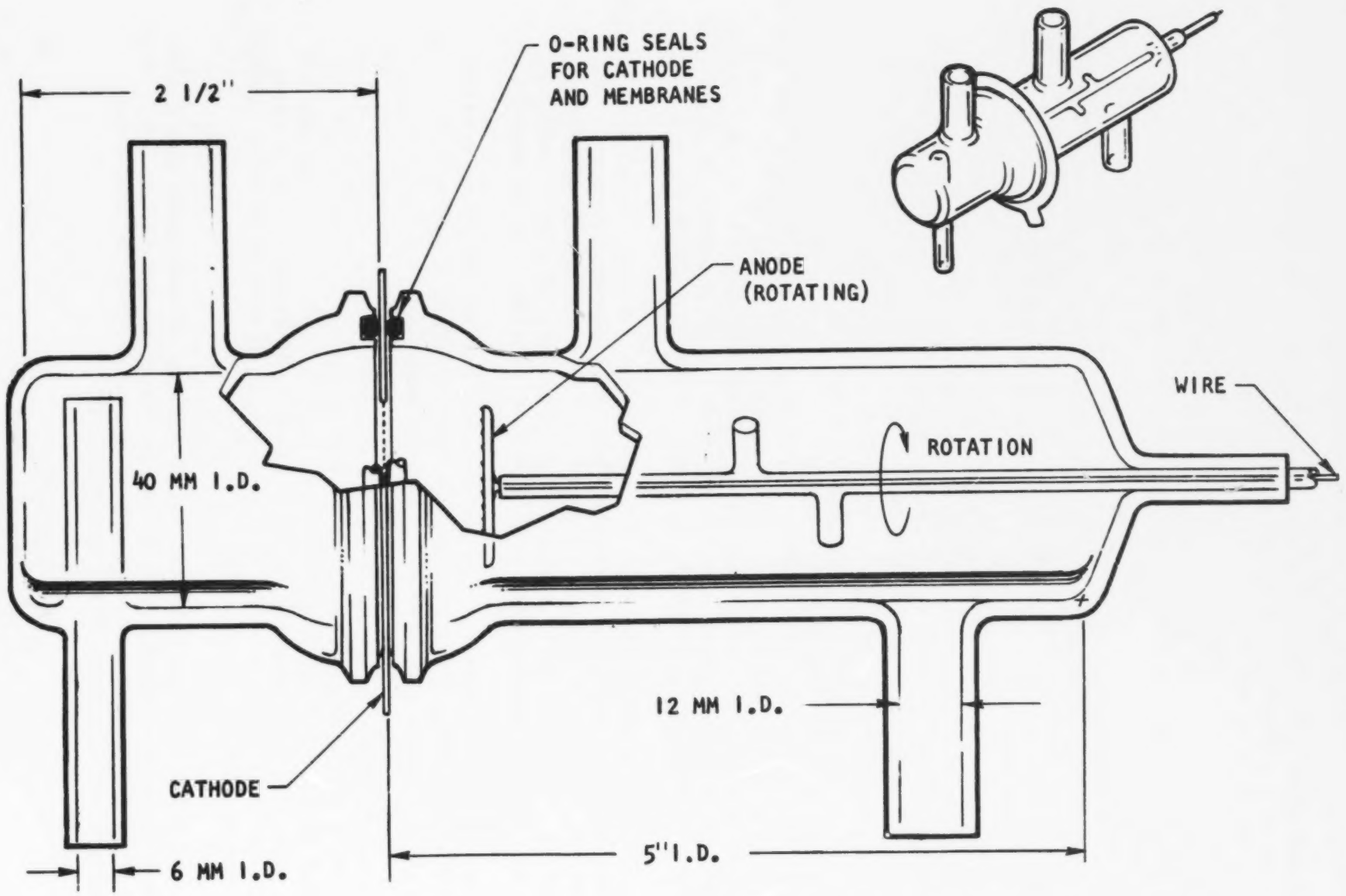


Figure 16. Electroosmotic Membrane Filter Cell

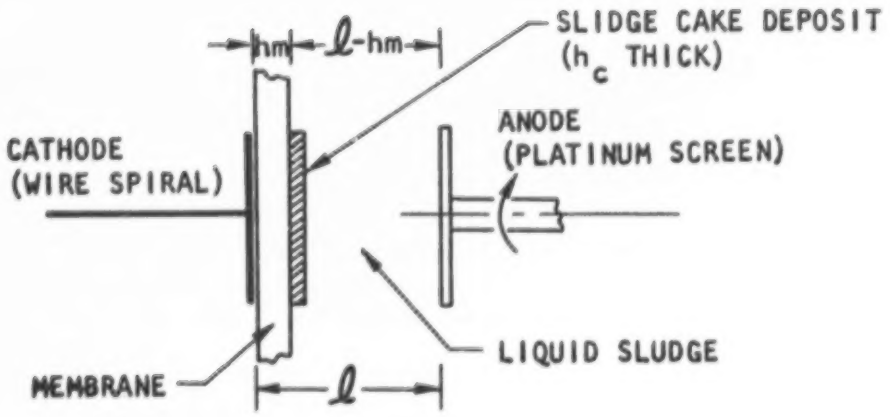


Figure 17. Membrane Location in Composite System

where Q and I are the volume flowrate and current, respectively. A is the cross-sectional area of the membrane, and v/d is the voltage gradient. For a composite medium, i.e., membrane and liquid sludge (and in some cases also an adhering sludge cake), the total resistance, R, is the sum of the individual layer resistances, and I and Q are constant throughout the cell. By means of the relation

$$R = h_m R_m + (\ell - h_m) R_s \qquad \text{II-3}$$

the membrane resistance R_m can be obtained from the layer widths and the liquid sludge resistance R_s. This latter quantity is given by

$$R_s = \frac{1}{AK_s} \qquad \text{II-4}$$

where K_s is the specific conductance of the liquid sludge (5.7×10^{-3} $(\text{ohm cm})^{-1}$). If, during a test run, a visible cake forms on the membrane surface, the effect of this layer may be taken into account by including an additional term, $h_c R_c$, on the right side of Eq. II-3 The permeability coefficient for the membrane, $(k_e)_m$, is obtained from Eq. II-1 and II-2 upon multiplying Q/I by R_m/A. Using this method of computation, one obtains the parameters for the individual membranes from the composite system data shown in Table XI.

The permeabilities, resistances, and power values (Ih_m/K_eA) shown for the individual membranes refer to a situation where the anode and cathode are in direct contact with the membrane surface. This would correspond to full utilization of the membrane properties for the water transport. However, the volume flowrate, Q, must be continuous throughout the cell. Because of this, if a sludge cake deposit forms on the membrane surface (which was found for the glass frit, ceramic SiO_2, and polyurethane foam), the amount of liquid reaching the membrane may be affected. Thus, depending upon the properties of the sludge cake formed, the true maximum flow through the membranes in the composite systems may not be achievable.

The data in Table XVI do indicate higher volume rate per consumed power for the sludge as a barrier material than for the membranes in the composite systems. Also, despite the large range in pore size (300,000Å to 24Å pore diameters) and the diversity in chemical properties, the power requirements do not seem to vary greatly for the individual membranes in the composite systems. Thus, it appears that the formation of sludge cake and penetration of sludge particles into the pores of the membranes may have, in fact, limited the attainable volume rate for a given power input.

TABLE XVI

ELECTROOSMOTIC DEWATERING DATA IN COMPOSITE SYSTEMS

Membrane Material	Composite Data					Derived Membrane Data			
	Volume Rate, $Q \times 10^{-3}$ ml/sec	$k_e \times 10^4$ cm sec^{-1} per v cm^{-1}	A, cm^2	R, ohm cm^{-1}	Power, watt-hrs / ml	$(k_e)_m \times 10^4$ cm sec^{-1} per v cm^{-1}	R_m, ohm cm^{-1}	h_m, cm	Power watt-hrs / ml
Sludge Cake	2.8	1.75	12.6	18.6	.26	.22	140	.1	.07
Glass Frit (M)	12.0	1.2	5.1	94.9	.28	.11	978	.15	.16
Ceramic (SiO_2)	6.4	.48	8.2	73.6	.45	.16	211	.8	.37
Polyurethane Foam	2.1	1.2	11.4	29.4	.33	.72	50	1.3	.21
Porous Teflon (Extra Coarse) (Chemware Teflon/ Halon)	2.4	.35	8.2	37.2	.42	.0074	1,775	8.9×10^{-3}	.09
Porous Teflon (Extra Fine)	7.5	.17	8.2	248	.82	.001	38,100	11.3×10^{-3}	.80
Dialysis Membrane Van Water & Rogers #25225	1.0	.17	8.2	32.7	.82	.0012	4,670	4.6×10^{-3}	.28
Nalfilm D-40 Nalco Chem. Co., Chicago, Ill.	1.2	.88	11.4	16.7	.58	.015	1,000	8.4×10^{-3}	.10

Control experiments were performed by using an aqueous NaCl solution (3,500 ppm NaCl) to ascertain if the sludge limits the flow through the membranes tested. The NaCl solution had approximately the same specific conductance as the sludge, and the membrane parameters were calculated in the way described for the sludge experiments. Table XVII shows the data obtained. The results with the NaCl solutions appear to confirm that the properties of the sludge determine the transport of water through the membranes. For the porous teflon extra coarse membrane, even the flow direction changes when NaCl solution is used. For the dialysis membrane, no water transport appeared to take place with NaCl solution while a small flowrate was measured with the sludge. For the glass frit, a more favorable volume rate/power was obtained with the salt solution than with the sludge.

In general, it is to be noted that in these experiments with NaCl solution, one finds a greater variation of flowrates (and directions) from one membrane to the next than in the runs with the sludge. This is in accord with the variety of membrane materials tested which range from hydrophobic to hydrophilic and from high to low porosity. The lack of such changes through the series of membranes investigated with the sludge points to the probability that the sludge surface properties become controlling even in cases where sludge cake formation at the membrane surface cannot be visually observed. We attribute such behavior to the adsorption of sludge solids onto the membrane pore surfaces, thus imparting the surface characteristics of the sludge solids to the membrane. Based on these data, it was concluded that no advantage could be gained through use of supplementary filter media.

TABLE XVII

ELECTROOSMOTIC DEWATERING DATA FOR NaCl SOLUTIONS(1)

Membrane Material	Composite Data					Derived Membrane Data			
	Volume Rate, Q x 10^{-3} ml/sec	k_e x 10^4 cm sec^{-1} per v cm^{-1}	A, cm^2	R, ohm cm^{-1}	Power, watt-hrs/ml	$(k_e)_m$ x 10^4 cm sec^{-1} per v cm^{-1}	Rm, ohm cm^{-1}	h_m, cm	Power, watt-hrs/ml
Glass Frit (M)	7.3	1.3	5.1	50.5	.26	.17	379	.15	.11
Porous Teflon (Extra Coarse) (Chemware Teflon/ Halon)	2.8 Reverse Dir.	.25	8.2	64.0	(.53)	.019	8400	8.9×10^{-3}	(.035)
Dialysis Membrane (Van Waters & Rogers #25225)	0								
Nalfilm D-40 (Nalco Chem. Co., Chicago, Ill.)	.52	.12	8.2	23.8	1.4	.0023	1240	8.4×10^{-3}	.27

(1) 3500 ppm

(2) Reversed Polarity

* U.S. GOVERNMENT PRINTING OFFICE : 1970 O - 411-103